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DESCRIPCIÓN

LÁSER DE FIBRA PULSADO ASISTIDO POR CONTROL DE POLARIZACIÓN

OBJETO DE LA INVENCIÓN

El objeto principal de la presente invención es un láser pulsado de fibra con anclado de modos, en configuración de anillo o de cavidad cerrada por reflectores, con alguna forma de absorbente saturable, y que comprende una etapa de amplificación basada en fibra dopada, en la que se aplica control de la polarización sobre la señal para modificar la respuesta del amplificador, de modo que se pueden optimizar la ganancia, ancho temporal y ancho espectral de los pulsos de salida.

ANTECEDENTES DE LA INVENCIÓN

En la actualidad existen numerosas aplicaciones para las fuentes de radiación ultrarrápidas, como el procesado de materiales, las telecomunicaciones o la tomografía óptica computerizada, lo cual ha dado lugar a una intensa actividad investigadora en el campo.

Entre las distintas opciones presentes para la implementación de fuentes ultrarrápidas, destacan aquellas que hacen uso de fibra óptica y anclado pasivo a los modos resonantes de la cavidad láser. Algunos ejemplos típicos utilizan configuraciones en anillo de fibra, o cavidades de fibra retroalimentadas por reflectores en sus extremos. En todos estos casos, el láser ultrarrápido requiere de un elemento amplificador en su interior, que puede ser también de fibra, y de algún tipo de absorbente saturable, que lleva a la formación de los pulsos ultracortos.

De entre las posibles configuraciones para la implementación del absorbente saturable en el dispositivo láser, la más simple y eficiente es la de usar un espejo semiconductor de absorbente saturable. Se han propuesto a lo largo del tiempo distintos materiales y estructuras como atenuadores, como por ejemplo grafeno, nanotubos de carbono, nanopartículas doradas, fósforo negro o aislantes topológicos, entre otros.

Habitualmente, estos láseres requieren, para su funcionamiento, del uso de fibra mantenedora de polarización. Por ello, el ajuste del estado de polarización en el interior del láser es algo habitualmente a evitar. Igualmente, se considera que el efecto de la polarización de la señal en el rendimiento de los amplificadores de fibra, comúnmente conocido como "polarization hole burning" ha de minimizarse o evitarse por completo, ya que resulta poco predecible y perturba las condiciones de trabajo del láser.

DESCRIPCIÓN DE LA INVENCIÓN

La presente invención se centra en un láser de fibra pulsado asistido por control de polarización que permite cambiar el estado espectral, incrementar la energía y reducir la anchura temporal de los pulsos ultracortos en dicho láser de fibra ultrarrápido, a partir de la modificación controlada de las propiedades de polarización de la luz antes de la inserción de esta luz modificada en un amplificador de fibra dopada.

Ajustando la polarización de la señal de forma óptima mediante un polarizador lineal y un controlador de polarización (o usando otro módulo de control de la polarización, como la atracción no lineal) es posible modificar la respuesta espectral y la ganancia del amplificador, lo que repercute en las propiedades del pulso de salida. La invención permite reducir notablemente la duración de los pulsos e incrementar la potencia de pico máxima de salida.

La invención puede utilizarse en cualquier cavidad de láser de fibra, ya sea delimitada por reflectores o en configuración de anillo, que comprenda amplificadores de fibra dopada, requiera o no el láser inicialmente del control del estado de polarización de la señal.

Particularmente, la cavidad del láser de fibra en configuración de anillo comprende un absorbente saturable, un módulo de control de polarización a continuación del absorbente saturable, y un amplificador de fibra dopado, situado a continuación del módulo de control de polarización.

El módulo de control de polarización puede presentar distintas configuraciones. En un primer aspecto comprende un polarizador seguido de un controlador del estado de polarización. El polarizador puede ser o no lineal. En un segundo aspecto, el módulo de controlador de polarización comprende un controlador mecánico del estado polarización. En un tercer aspecto, el módulo de control de polarización comprende un controlador mecánico basado en atracción no lineal de polarización. En este tercer aspecto de la invención, el controlador mecánico basado en atracción no lineal de polarización puede estar precedido por un polarizador, que puede ser o no lineal.

El láser de fibra puede comprender además un acoplador de fibra, que permite caracterizar los pulsos de salida del láser, que se examina en un módulo de análisis, como puede ser un medidor de potencia, un autocorrelador, un analizador de espectro óptico (OSA, Optical Spectrum Analyzer), un osciloscopio (OC) o un analizador de espectro eléctrico (ESA, Electrical Spectrum Analyzer).

De esta forma, ajustando el estado de polarización de la señal de forma óptima mediante el uso del módulo de control de polarización, ya sea mediante procedimientos mecánicos o haciendo uso de las propiedades no lineales de la fibra, es posible modificar la respuesta espectral y de ganancia del amplificador de fibra dopada de forma que, lejos de producir un efecto negativo, permite un grado de libertad adicional en el control de la respuesta del amplificador, que repercute en las propiedades del pulso de salida. El módulo de control de polarización, inicialmente contraintuitivo, permite, en las condiciones adecuadas, reducir notablemente la duración de los pulsos e incrementar la potencia de pico máxima de salida.

Las potenciales aplicaciones de la tecnología incluyen la generación de señales de amplio espectro para la monitorización ambiental (ampliables en la detección de contaminantes atmosféricos o acuáticos, por ejemplo), la fabricación de fuentes LIDAR, láseres para marcado o procesado de materiales y la creación de peines de frecuencia, entre otras.

DESCRIPCIÓN DE LOS DIBUJOS

Para complementar la descripción que se está realizando y con objeto de ayudar a una mejor comprensión de las características de la invención, de acuerdo con un ejemplo preferente de realización práctica de la misma, se acompaña como parte integrante de dicha descripción, un juego de dibujos en donde con carácter ilustrativo y no limitativo, se ha representado lo siguiente:

Figura 1.- Muestra una primera realización del láser de fibra pulsado de la invención.

Figura 2.- Muestra una segunda realización del láser de fibra pulsado de la invención.

Figura 3.- Muestra una tabla con las mejoras obtenidas sobre sistemas de láser de anillo en función de la longitud de la cavidad.

REALIZACIÓN PREFERENTE DE LA INVENCIÓN

Se describe a continuación, con ayuda de las figuras 1 a 3, una realización preferente del láser de fibra pulsado asistido por control de polarización.

Como se muestra en las figuras 1 y 2, la cavidad del láser (1) de fibra en configuración de anillo objeto de la presente invención comprende un absorbente saturable (2) que funciona para cualquier estado de polarización de la señal, un módulo de control de polarización (3), a continuación del absorbente saturable (2), y un amplificador de fibra dopado (4), situado a continuación del módulo de control de polarización (3). Todos estos elementos se encuentran unidos por unos tramos de fibra.

El módulo de control de polarización (3) puede presentar distintas realizaciones. En un primer aspecto comprende un polarizador seguido de un controlador del estado de polarización. El polarizador puede ser o no lineal. En un segundo aspecto, el módulo de controlador de polarización (3) comprende un controlador mecánico del estado polarización. En un tercer aspecto, el módulo de control de polarización (3) comprende un controlador mecánico basado en atracción no lineal de polarización. En este tercer aspecto de la invención, el controlador mecánico basado en atracción no lineal de polarización puede estar precedido por un polarizador, que puede ser o no lineal.

El láser (1) puede comprender además un acoplador de fibra (5), que permite caracterizar los pulsos de salida del láser (1), que se examinan en un módulo de análisis (6, 7), como puede ser un medidor de potencia, un autocorrelador, un analizador de espectro óptico (OSA, Optical Spectrum Analyzer), un fotodiodo seguido de un osciloscopio (OC) o un analizador de espectro eléctrico (ESA, Electrical Spectrum Analyzer).

En una primera realización de la invención, mostrada en la figura 1, el láser (1) de fibra utiliza una configuración de anillo, donde la luz se propaga en sentido contrario a las agujas del reloj. En este caso, el absorbente saturable (2) es un espejo de semiconductor de absorbente saturable. Además, el módulo de control de polarización (3) se dispone antes del amplificador de fibra dopado (4) que está dopado con erbio.

En una segunda realización de la invención, mostrada en la figura 2, el láser (1) de fibra utiliza una configuración de anillo ultralargo por medio de una cavidad extendida (8) gracias a una fibra óptica, donde la luz se propaga en sentido contrario a las agujas del reloj. Al igual que en el caso anterior, el absorbente saturable (2) es un absorbente saturable de semiconductor en configuración de espejo (SESAM). La cavidad extendida (8) se coloca entre el absorbente saturable (2) y el módulo de control de polarización (3). A continuación de este se sitúa el amplificador de fibra dopado (4), dopado también con erbio en este caso. Después del amplificador de fibra dopado (4) se encuentra el acoplador de fibra (5), que facilita la extracción de los pulsos de salida.

En un aspecto de la invención, el láser (1) comprende adicionalmente un circulador óptico que conecta el absorbente saturable (2) a la cavidad láser (1).

En un aspecto de la invención, el láser (1) puede comprender adicionalmente un aislador a la salida del amplificador de fibra dopada (4).

En un aspecto de la invención, la cavidad extendida (8) puede tener amplificación propia asistida por efecto Raman.

La figura 3 muestra una tabla con las mejoras obtenidas sobre sistemas de láser de fibra en configuración de anillo cuando hay control de polarización, para diferentes longitudes de la cavidad extendida. Los resultados con control de polarización son los que se marcan en cursiva y subrayados, y como se puede comprobar, suponen una mejora significativa, pues se obtienen pulsos de menor ancho temporal, mayor potencia de pico y mayor es la ganancia del amplificador dopado con Erbio (EDFA).

REIVINDICACIONES

1.- Láser (1) de fibra pulsado asistido por control de polarización, que comprende un absorbente saturable (2) y un amplificador de fibra dopado (4), caracterizado porque comprende adicionalmente un módulo de control de polarización (3) dispuesto entre el absorbente saturable (2) y el amplificador de fibra dopado (4).

2.- El láser (1) de la reivindicación 1, donde el módulo de control de polarización (3) comprende a su vez un polarizador seguido de un controlador del estado de polarización.

3.- El láser (1) de la reivindicación 2, en el que el controlador del estado de polarización es un controlador mecánico del estado de polarización.

4.- El láser (1) de la reivindicación 1, en el que el módulo de control de polarización (3) está basado en la atracción no lineal de polarización.

5.- El láser (1) de la reivindicación 1, en el que el módulo de control de polarización (3) comprende un polarizador seguido de un controlador de polarización basado en la atracción no lineal de polarización.

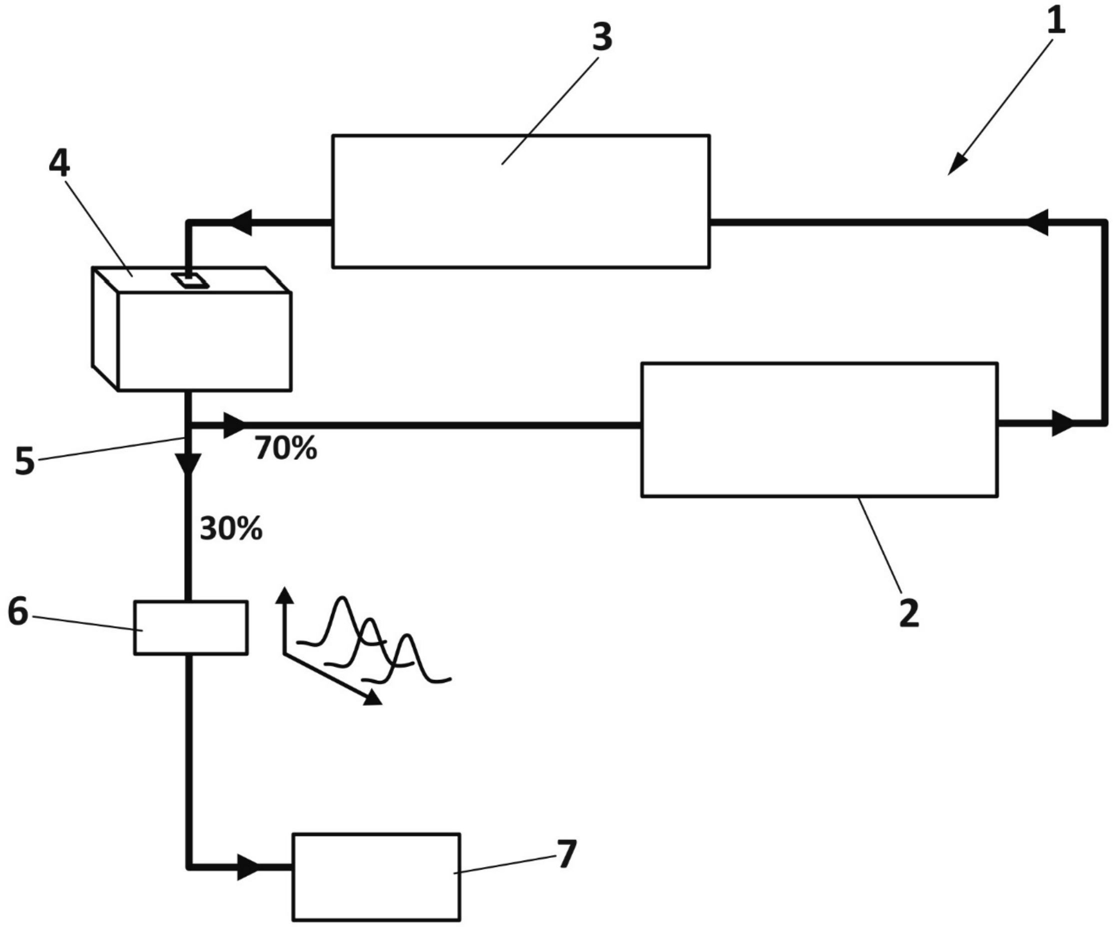

FIG. 1

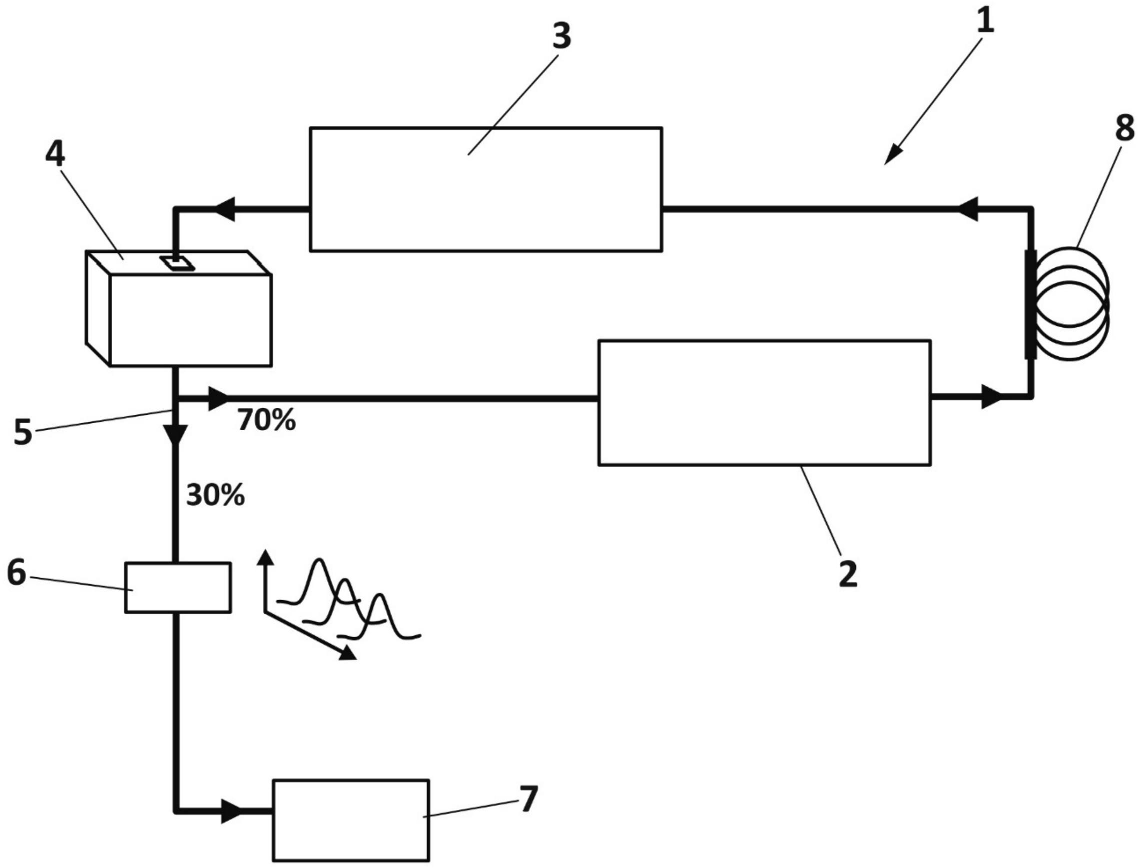

FIG. 2

Longitud de la cavidad (m)	Ancho temporal (fs)	Potencia de pico (MW)	Ganancia EDFA (dB)	Diferencia de ganancia (dB)
30.8	303 *166*	0.06 *0.10*	14 *14.4*	0.4
324	336 *178*	0.59 *0.95*	18.9 *20.8*	1.9
1010	269 *172*	1.70 *2.54*	22.1 *25*	2.9
2400	302 *193*	2.68 *4.97*	25.6 *31.7*	6.1

FIG. 3

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[0001] BACKGROUND OF THE INVENTION 1. Field of the Invention The present invention relates to a high power optical fiber femtosecond laser generated by nonlinear polarization rotation and coupled mode locking of a saturated absorber, and more particularly, to an optical fiber resonator capable of outputting a high output femtosecond laser pulse through a mode lock.

[0002] The fiber-based femtosecond laser resonator can be classified into a ring-type, a figure-eight type, and a Fabry-Perot type according to the shape of a resonator. In the ring type, passive mode locking is realized by using a saturable absorber exhibiting nonlinear polarization rotation and different transmission and absorption characteristics depending on the amount of light to generate a narrow pulse. In the case of the Fabry-Perot type, unlike a circular resonator, a narrow pulse is generated mainly by using a saturable absorber mirror since the traveling direction of the pulse in the resonator is bidirectional. On the other hand, in the case of the 8-shape, two resonant loops are connected through a fiber coupler, and a narrow pulse is generated using the difference between nonlinear phenomena in the clockwise and counterclockwise pulses.

[0003] The fiber optic femtosecond laser is mostly composed of a unidirectional ring cavity composed of a single mode fiber (SMF) and a rare earth doped fiber (gain medium), which reduces backscatter This makes it possible to operate the turnkey system easily because of self-starting easily, and it is possible to operate for a long time by insensitivity to environmental changes. It is possible to use the optical fiber components in the communication band at a low price, It has several advantages that are suitable for industrial application.

[0004] As a typical gain medium, an erbium doped fiber (EDF) having an absorption band of 980 nm or 1480 nm as a absorption band and a broad emission band around a wavelength of 1550 nm, and an absorption band of 980 nm, Ytterbium doped fiber (YDF) having a wide emission band of the rare earth doped fiber (YDF) is generally used. In addition, a rare earth doped fiber such as Thulium, Holmium, Neodymium, Praseodymium etc. forming a gain in a different wavelength band) Is used.

[0005] Since the rare-earth doped optical fiber is a gain medium having a wide wavelength bandwidth, 105 to 106 frequency modes having intervals corresponding to the repetition rate are amplified in the gain medium to form an optical comb, To form a narrow pulse.

[0006] The passive mode locking of fiber-optic femtosecond lasers is generally done in three ways using nonlinear polarization rotation (NPR), saturable absorber (SA), and nonlinear amplifying loop mirror (NALM) It is divided.

[0007] The manual mode locking scheme will be described in more detail below.

[0008] Mode locking using nonlinear polarization evolution is based on a nonlinear effect that occurs when elliptically polarized light passes through a Kerr medium.

[0009] The nonlinear Kerr rotation describes the refractive index, n, of the single mode optical fiber, which varies with the intensity of light, I, as a result of which the vertical component electric field of different intensities of elliptically polarized light And the horizontal component electric field pass through the single mode optical fiber, and the phase difference between the two electric fields is generated and the main axis of the elliptically polarized light is rotated.

[0010] Here, the role of each part of the rare-earth-doped fiber laser and the phenomenon occurring in order to perform mode locking by the nonlinear polarization rotation phenomenon will be sequentially described.

[0011] If the output of the pumping laser is increased in accordance with the absorption band of the rare earth doped optical fiber, which is a gain medium in the resonator, spontaneous emission is caused to the emission band of the gain medium. At this time, the naturally emitted light acts as white noise and is amplified by reciprocating in the resonator. If the portion of the amplified white noise having the highest intensity exceeds the loss caused by reciprocation in the resonator, a small pulse is generated and the pulse is amplified to self-start. The pulse generated inside the resonator is linearly polarized by a polarizer and passes through the first polarization controller and is converted to elliptical polarized light. The elliptically polarized light formed by the polarization controller has a phase velocity and a light intensity which are different from each other in the vertical component electric field and the horizontal component electric field. The nonlinear effect generated through the single mode optical fiber, which is a core, Rotation. Since the refractive index is a function of the intensity of light as shown in the equation, the degree of rotation of the elliptical polarized light changes in a portion where the intensity of light near the center of the pulse is strong and a portion where the intensity of light at both edges is weak. The pulse of the rotated elliptical polarization is amplified in the rare earth doped optical fiber, which is a gain medium. The amplified pulse is again passed through a single mode fiber, which is a Kerr medium, and is subjected to a rotation of a larger elliptically polarized light, and is converted to a linearly polarized light pulse by a second polarization controller. At this time, the elliptically polarized main axis of the strong part of the pulse and the weak part of the pulse are adjusted perpendicular to each other by using a polarization controller, and then converted into linearly polarized light. The pulse of linearly polarized light is incident on the polarizer again and the polarizing direction of the polarizer coincides with the polarizing direction of the strong portion of the pulse light so that a minimum loss occurs in the portion where the light intensity of the pulse is strong, A large loss occurs in a portion where the intensity of light is weak, thereby producing a pulse of a narrow width.

[0012] In other words, the nonlinear polarization rotation mode locking condition is a condition for forming an artificial saturable absorber capable of eliminating a weak portion of a pulse edge due to a strong portion of a pulse centered by a polarizer inside the resonator. . The nonlinear polarized rotation type mode locking is advantageous in that it can self-oscillate for mode locking from white noise without any special device, can be constructed with optical fiber products with relatively low communication bandwidth without a limited lifetime, & Lt; / RTI & > The disadvantage is the mode locking using the polarization change inside the optical fiber, so it is necessary to stabilize the temperature of the optical fiber constituting the resonator for the stable polarization state.

[0013] Next, a mode lock using a saturable absorber will be described. The saturable absorber utilizes a phenomenon in which the absorption of light decreases when the intensity of light is increased. Since the intensity of light traveling through the resonator is weak, the saturable absorber is absorbed through the saturable absorber, While the middle part of the pulse acts as a nonlinear filter capable of continuing the inside of the resonator by saturating the absorption in the saturated absorber due to strong intensity of the light so that the mode lock having a narrow pulse width .

[0014] Types of saturable absorbers used in mode locking include semiconductor saturable absorbers, carbon nano tubes, and graphene. The advantage of mode locking using a saturated absorber is that it can generate pulses more easily than other mode locking methods, can form a short-length resonator, can form a femtosecond laser with a high repetition rate, The influence of the polarization change is small. Disadvantages include absorber damage threshold at mW level, limited lifetime, and limited pulse widths of several hundred fs that can be reduced with relaxation time.

[0015] Mode locking using a nonlinear amplifying loop mirror is a mode locking method used in an 8-shaped resonator. This is a system in which two resonant loops are connected through a fiber coupler. The amplification positions of the pulses traveling in the clockwise direction and the counterclockwise direction are made different or the coupling ratios are made different, Causing a difference.

[0016] At the point where the two pulses meet, the middle part of the pulse having strong intensity of the light through the interference becomes the constructive interference, and the transmission of the light is maximized. On the other hand, the edge part of the pulse having weak light intensity induces destructive interference, , Which is a mode locking method that induces a narrow pulse width. The advantage is that it is possible to generate a pulse with a high energy and a narrow width by using a long resonator length, but it is disadvantageous in that it is difficult to form a femtosecond laser having a high repetition rate because a long resonator length is required.

[0017] The factors that determine the mode locking of fiber-based femtosecond lasers are polarization, pumping power, nonlinearity, and dispersion. By adjusting these four factors, a stable mode lock can be realized because the mode lock condition is satisfied. These four elements are closely related to each other, and when controlling each element, they affect other elements, and therefore, they are mutually restrictive. The role of each element in optical fiber femtosecond laser mode locking is summarized as follows.

[0018] Polarization is controlled by the degree of nonlinear polarization generated by the nonlinear phenomenon in the polarization controller and Kerr medium inside the resonator, which leads to a polarization state suitable for mode locking. The polarization controller is located before and after the polarizer and is composed of a wave plate or a combination of optical fiber type polarization controller which twists or pushes the optical fiber. Since the wave plate is rotated or birefringence is formed in the optical fiber, It can be controlled manually. Also, by adjusting the amount of light by controlling the pump output and the polarization before the polarizer, the degree of nonlinear polarization rotation in the medium is controlled to adjust the polarization state satisfying the mode locking condition.

[0019] As described above, the pump power controls the nonlinear polarization rotation due to the nonlinear phenomenon in the kerr medium, and regulates the gain inside the resonator. That is, when the polarization state of the polarization controller in the resonator is fixed, the mode lock can be induced by controlling the non-linear polarization rotation by controlling the pump output. If the mode locking condition can be satisfied by only the nonlinear polarization rotation by the pump output, it is not necessary to use a polarization controller inside the resonator. However, since the inside of the optical fiber is not uniform and the optical fiber is bent during the resonator configuration, It is difficult to find the mode lock condition without the polarization controller. If the pump output is continuously increased while the mode is locked, the gain of the non-pulse will be increased, and the amplification of the pulse in the gain medium will saturate, while the amplification of the noise component will be increased to generate multiple pulses Respectively. As a result, the mode lock state can not be maintained beyond the polarization state satisfying the mode lock condition.

[0020] Nonlinearity is an important factor for forming a mode locking condition by generating nonlinear polarization rotation in a resonator. It is controlled by adjusting the amount of light by controlling the pump output and the polarization before the polarizer, It plays a role.

[0021] Dispersion can be controlled by a combination of the lengths of the optical fibers having different sign and size dispersion forming the resonator, and the dispersion can be controlled, so that the characteristics of the pulse generated in the resonator can be controlled. A soliton fiber laser is formed when the dispersion of the entire resonator is controlled so that the dispersion is an anomalous dispersion region where the dispersion is negative and the dispersion is a normal dispersion normal dispersion region forms a self-similar fiber laser, and when the total dispersion is zero dispersion, a dispersion managed fiber laser is formed.

[0022] Next, classification of optical fiber femtosecond laser according to total dispersion is as follows.

[0023] The soliton laser is a nonlinear phase delay (nonlinear phase delay) caused by a nonlinear phenomenon, which is a condition for forming pulses, by a dispersion phase delay caused by anomalous dispersion of a single mode optical fiber) To maintain a constant pulse state. In other words, the pulse can not be maintained because the dispersion and balance of the optical fiber can not be achieved due to the increase of the nonlinear phenomenon at the high energy state. Therefore, the soliton pulse laser has a limitation on the formation of a broad spectrum because of limited pulse width and power that can be generated and limited nonlinear phenomenon.

[0024] In a dispersion managed laser, the dispersion phase delay of a normal dispersion fiber is equal to the dispersion phase delay of an ideal dispersion fiber. Therefore, the pulse width is breathing in the resonator and forms a pulse. That is, since the width of the pulse is breathing inside the resonator, it is possible to suppress the pulse breaking due to the excessive nonlinear effect in the high energy state of the resonator, so that the high output and the broad spectrum can be formed. In addition, it has recently been reported that the resonator intensity and timing noise are very low, which is considered as a type suitable for precision measurement and processing applications.

[0025] A self-similar laser forms a steady pulse with a constant width because the continuously increasing pulse width due to fiber dispersion is reduced due to frequency bandwidth limitations of the gain medium and frequency filtering by nonlinear polarization rotation mode locking. Since the optical fiber dispersion and the nonlinear phenomenon, self-phase modulation, generate chirps of positive (+) pulses, the pulses formed in the resonator have a wide width and therefore have high output without excess nonlinear phenomenon. Self-similar lasers have high resonance intensity and timing noise, and require an external dispersion compensator to form narrow pulse widths.

[0026] On the other hand, in order to generate an optical fiber femtosecond pulse satisfying the characteristics of an average power of 100 mW or more, a pulse energy of 3 nJ or more, and a pulse width of 100 fs simultaneously, an amplifier and an external dispersion compensator are additionally required in addition to a resonator. In this case, the system is complicated and the cost is increased, which is a disadvantage in the application of the industrial field. Further reduction of the stability of the surrounding environment caused by the addition of the system and increase of the noise generated by the amplifier cause limitations in the application of the precision field.

[0027] To describe the output, energy, and pulse width limits of a nonlinear polarized rotation mode locked or saturated absorber mode locked fiber femtosecond laser using only a resonator to generate a femtosecond pulse, a fiber optic femtosecond laser with nonlinear polarization rotation mode locking has a total dispersion In the case of a soliton laser in the negative domain, it is possible to generate a narrow pulse at a level of 100 femtoseconds, while a pulse with a high peak output is kept constant inside the resonator, so that the pulse is separated by an excessive nonlinear effect Distortion is easily generated and has a pulse energy limit of 0.1 nJ.

[0028] In the case of a dispersion-controlled (soliton) laser with a total dispersion close to 0, it induces the expansion and contraction of the pulse width to suppress excess nonlinear phenomenon, thereby inducing an increase in pulse energy. However, .

[0029] In addition, soliton and dispersion-controlled soliton lasers produce dispersive waves in addition to the main pulses, reducing the energy concentration of the main pulses over time.

[0030] In addition, although the femtosecond laser of the optical fiber by the saturable absorber mode locking can generate pulse energies of several nJ or more, it has a pulse width limit of hundreds of femtoseconds, and the frequency bandwidth of the optical comb is also formed to be as narrow as 10 nm.

KR 10-0957133 KR 10-1155541

SUMMARY OF THE INVENTION Accordingly, the present invention has been made to solve the above-mentioned problems occurring in the prior art, and it is an object of the present invention to provide a hybrid mode locking method that combines a nonlinear polarization rotation mode locking method and a saturated absorber mode locking method. The narrow pulse width of 100 fs and the pulse output and the energy limit at the same time in a single resonator without external amplifier and dispersion compensator are induced by inducing the narrow nonlinear phenomenon suppression in the gain medium by narrow femtosecond pulse generation and nonlinear filtering of the saturated absorber. The goal is to produce a high power optical fiber femtosecond laser with over 100mW output, energy over 3nJ, and high energy concentration in the main pulse by suppressing the dispersion wave by saturating absorber.

According to an aspect of the present invention, there is provided an optical fiber femtosecond laser resonator including: a ring-type optical fiber-based resonator including a laser source; a resonator formed on the resonator; A nonlinear polarization rotation mode lock unit for generating a super short pulse and nonlinear filtering of the pulse amplitude, suppressing excess nonlinear phenomenon in the resonator, generating an initial pulse, and generating a parasitic dispersion wave generated from a soliton pulse, The polarized light rotation mode locking unit is composed of an optical port, a polarization controller, a polarization beam splitter (PBS), a polarization controller, and an optical port in this order. . The polarization controller is composed of a half wave plate and a quarter wave plate. The transmission mode saturated absorber may include a semiconductor saturable absorber, a carbon nanotube (hereinafter, referred to as & quot; absorber & quot;), an optical connector, a transmission type saturable absorber and an optical connector. carbon nanotubes, graphene, etc. Also, the resonator may be a single-mode optical fiber using a medium for nonlinear polarization rotation of pulses, a rare-earth doped optical fiber using a gain medium, The resonator further comprises an optical coupler for an output end of the resonator, and the resonator further comprises an optical coupler for emitting a pulse reflected from the polarization beam splitter The nonlinear polarization rotation mode lock unit may include a nonlinear polarization rotation mode lock unit, The nonlinear polarization rotation mode locking unit is composed of a polarization rotation mode lock unit based on an optical fiber, and the optical fiber-based polarization control unit and the optical fiber- A substrate polarizer, and an optical fiber-based polarization controller. The optical fiber substrate polarization controller adjusts the optical fiber by winding the optical fiber around a plurality of paddles, rotating the optical fiber, or squeezing and pressing the optical fiber. The saturable absorber mode locking unit may include an optical fiber circulator for transmitting a pulse that has entered the input end, a light receiving unit for receiving light transmitted to the optical fiber circulator, An optical port for collimating or focusing and a nonlinear filtering of pulses incident through the optical port The polarized beam splitter configured in the non-linear polarized rotation mode lock unit is configured to receive a pulse transmitted therethrough, and the saturable absorber mode lock unit is configured to receive the pulse transmitted through the polarization beam splitter, The absorber mode locking portion is constituted by a single? / 4 wave plate and a saturated absorber. The resonator has a diffraction grating (between the nonlinear polarization rotation mode locking portion and the saturable absorber mode locking portion) Thereby controlling the overall dispersion of the resonator.

The present invention configured as above generates a high output femtosecond pulse having a high energy concentration and an optical comb of a wide wavelength band with high stability using only a single optical fiber resonator having a simple and economical structure. Therefore, astronomical spectrograph calibrations, It can be used for precision applications such as remote distance ranging and coherent LIDAR, industrial applications such as shape measurement and processing, and optical fiber femtosecond for precision industrial applications such as broadband spectroscopy, remote sensing, There is an advantage that a laser can be easily applied.

[0049] FIG. 1 is a block diagram of a hybrid mode lock resonator in which a linear nonlinear polarization rotating portion and an optical fiber-based transmission type saturated absorber are combined. FIG. 2 is a view showing an optical spectrum of an optical comb generated in a hybrid mode locked resonator, FIG. 3 shows an optical spectrum of an optical comb and an auto-correlation signal of a pulse generated in a NPR-dominating mode locked resonator, FIG. 5 is a graph of the RF spectrum of the hybrid mode locked high output fiber laser repetition rate and the variation of the stabilized repetition rate frequency with time, FIG. 6 is a graph of the energy concentration of the hybrid mode locked pulse and the nonlinear polarization rotation dominant mode locked pulse, A hybrid mode lock resonator configuration in which the polarized light splitter 102 of Fig. 1 is replaced by a polarizer 600 and an optical fiber output stage 602, 8 is a hybrid mode locking resonator configuration in which a linear nonlinear polarization rotating portion and a bulk saturation absorber are combined, FIG. 9 is a view showing a hybrid mode locking resonator in which a bent path nonlinear polarization rotating portion and a bulk saturation absorber FIG. 10 is a configuration diagram of a hybrid mode lock resonator capable of real time dispersion adjustment. FIG.

[0050] DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS Hereinafter, a preferred embodiment of a high power optical fiber femtosecond laser produced by coupling mode locking of nonlinear polarization rotation and saturable absorber according to the present invention will be described in detail with reference to the accompanying drawings.

[0051] The high output optical fiber femtosecond laser generated by the nonlinear polarization rotation and the coupling mode locking of the saturable absorber according to the present invention can be used for an optical fiber femtosecond laser resonator in which an optical fiber based resonator of a ring- 10), which is configured on the resonator, performs nonlinear polarization rotation mode locking and pulse amplitude nonlinear filtering to generate an ultrashort pulse by pulse shaping, suppresses excess nonlinear phenomena in the resonator, And a saturable absorber mode locking portion for performing generation of a pulse and removal of a parasitic dispersion wave generated in a soliton pulse.

[0052] The femtosecond laser according to the present invention includes a resonator composed of optical fiber based components, a nonlinear polarization rotation mode lock unit 100 for generating a narrow width ultrashort pulse by pulse shaping, and a nonlinear filtering effect of pulse amplitude, And a saturable absorber mode locking unit 101 for suppressing nonlinear phenomenon, easily generating an initial pulse, and eliminating a parasitic dispersion wave generated in a soliton pulse, and is provided with a clean high-energy-concentrated single high- The main technical point is to generate short pulses.

[0053] DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS The present invention will be described in detail below with reference to the accompanying drawings.

[0054] BRIEF DESCRIPTION OF THE DRAWINGS FIG. 1 is an overall configuration diagram of a high output optical fiber femtosecond laser resonator generated by nonlinear polarization rotation and coupled mode locking of a saturated absorber according to the present invention. The resonator according to the present invention largely consists of a portion of the optical fiber resonator 10, a nonlinear polarization rotation mode lock portion 100, and a saturated absorptive mode lock portion 101 in order to generate a high output pulse.

[0055] The optical fiber resonator is a ring type and has a ring cavity structure. The optical fiber resonator is composed of a rare-earth doped optical fiber 110 for use as a gain medium and a laser corresponding to an absorption light wavelength of the gain medium A diode 109, a wavelength division multiplexer 108 for passing the light output from the laser diode through a gain medium, a single mode optical fiber 111 for use as a Kerr medium for nonlinear polarization rotation of pulses, An isolator 112 for reducing optical noise and generating a pulse in a unidirectional direction, and an optical coupler 601 for a resonator output stage.

[0056] The nonlinear polarized rotation mode locking unit 100 includes a polarization controller 103 configured by a combination of a plurality of half wave plates and a quarter wave plate, a polarization beam splitter 102 positioned in the polarization controller, And an optical port (104) provided on both sides of the wave plate for inputting / outputting light from the optical fiber constituting the resonator to the nonlinear polarization rotation mode lock part, for collimating and re-focusing the beam from the optical fiber, do. The non-linear polarization rotation mode lock part adjusts the wavelength plate with respect to the polarization axis of the polarization beam splitter 102 (PBS) to reach a polarization state for optimum mode locking. This can be automated through the implementation of the mode lock described in Korean Patent No. 10-1155541 entitled "Mode Lock Automation Device of Optical Fiber Femtosecond Laser".

[0057] The saturable absorber mode locking portion 101 is constructed by inserting a transmissive saturated absorber 106 between the optical connectors 107. The saturated absorber used may be a semiconductor saturable absorber or carbon nanotubes), And graphene. The saturated absorber has a relaxation time that is slower than the pulse width generated by the laser and has a saturation flux higher than that of the laser internal pulse fluence so that pulse generation and output attenuation are performed to eliminate excess nonlinearity in the gain medium If the saturation absorber saturates and does not play a role in pulse attenuation if the saturation fluorescence is lower than that of the laser internal pulse fluence while generating a hybrid mode lock of amplifiable high power, it is limited by the excess nonlinear phenomenon occurring in the gain medium Low-power nonlinear polarization rotation dominant mode lock.

[0058] 2 is a spectrum 200 and autocorrelation signal 201 of a hybrid mode locked erbium-doped fiber femtosecond laser in the dispersion-controlled soliton band. With a power of 156 mW and a pulse energy of 3.13 nJ, a spectrum having a wavelength bandwidth of 30 nm around 1570 nm and a clean pulse having a width of 146 fs in a time domain and having no dispersion wave are generated and high energy is concentrated on the main pulse Able to know.

[0059] FIG. 3 is a spectrum 300 and autocorrelation signal 301 of a non-linear polarization-dominant mode locked erbium-doped fiber femtosecond laser in the dispersion-controlled soliton band. The output is 41 mW, which is about 1/6 of that of the hybrid mode lock. It can be seen that the energy concentration is low due to the generation of the dispersion wave in addition to the main pulse in the time domain, which is seen as the Kelly side peak in the frequency spectrum .

[0060] FIG. 4 is an accumulated pulse energy comparison graph 400 and an accumulated pulse energy percentage comparison graph 401 for comparing the pulse energy concentration of the hybrid mode lock of FIG. 2 and the nonlinear polarization rotation dominant mode lock of FIG. 3, Approximately 98.5% of the energy of the mode-locked pulse is concentrated in the main pulse, whereas only 94% of the energy of the nonlinear polarization-dominant mode locked pulse is concentrated in the main pulse, indicating that the energy concentration of the hybrid mode locked pulse is high .

[0061] FIG. 5 is a graph of the RF spectrum 500 of the pulse repetition rate of the hybrid mode locked fiber femtosecond laser of FIG. 2 and the stabilized repetition rate frequency graph 501 over time, showing the generation of a higher order RF repetition rate and about 0.2 MHz standard deviation The interference and stability of the optical comb can be verified through the repetition rate stability.

[0062] 6 to 10 show another embodiment of the laser resonator according to the present invention, and will be described with reference to the drawings.

[0063] Fig. 6 illustrates the use of a polarizer 600 in place of the polarization beam splitter 102 configured in the nonlinear polarization rotation mode lock of Fig. 1 and the free space output stage 105 to an optical fiber based optical coupler 601 and an optical fiber output stage 602 in FIG. 1). Applying an optocoupler on the resonator and applying it to the output stage (replacing the free-space output stage 105 of Figure 1 with 602) replaced the beam splitter of the polarization rotation mode lock with a polarizer.

[0064] 7 is an all fiber laser in which all parts of the resonator are fiber optic, in which the volumetric nonlinear polarization rotation mode lock 100 of FIG. 1 is replaced by a fiber optic based polarization rotation mode lock 700, Controller 701 and an optical fiber-based polariser 702. The optical fiber- The optical fiber-based polarization controller adjusts the optical fiber by winding the optical fiber around a plurality of paddles or squeezing and pressing the optical fiber to realize a role of a wave plate.

[0065] FIG. 8 is a resonator in which the optical fiber based saturable absorber mode lock 101 of FIG. 1 is replaced by a saturable absorber mode lock 800 of a volume type. A pulse entering the input end of the optical fiber circulator 802 is transmitted through the optical port 104, And the pulse reflected by the saturated absorber is output to the output port of the optical port 104 and the optical fiber circulator 802 to circulate the resonator. The configuration of the nonlinear polarization rotation mode lock unit is implemented in the same manner as the configuration shown in FIG.

[0066] FIG. 9 is a sectional view of a polarized light path nonlinear mode lock unit 900 formed by folding the optical path of the linear polarized rotation mode lock unit 100 of FIG. 1 through the polarization beam splitter 102 and the volume type saturated polarizer mode lock unit 901) Is a hybrid resonator. The volume-type saturable absorber mode locking unit 901 includes a? / 4 wave plate 902 and a reflection type saturable absorber 801. The pulse reflected by the polarized light splitter is reflected by the saturated absorber and passes through the polarized light splitter So that the resonator is circulated.

[0067] 10 corresponds to a resonator configured to adjust the dispersion of the entire resonator by providing a diffraction grating 1002 inside the resonator. A beam splitter 1001 may be formed on one side of the resonator to reflect the circulating laser so as to realize dispersion compensation through the pair of diffraction gratings 1002. [In the case of the ytterbium-doped fiber laser, dispersion compensation by the diffraction grating 1002 is required as an element of the optical fiber having normal dispersion. Wherein the diffraction grating can be replaced by a prism.

[0068] In summary, the optical fiber femtosecond laser according to the present invention has a ring cavity structure and includes a nonlinear polarization rotation mode lock part composed of a wave plate and a polarizer for pulse shaping 100), a saturated absorber mode locking portion 101 for excess nonlinear phenomenon, dispersion wave suppression and easy initial pulse oscillation.

[0069] The resonator may include a rare earth doped fiber for use as a gain medium, a laser diode corresponding to an absorption light wavelength of the gain medium, a light source for emitting light output from the laser diode to a gain medium, Single mode fiber (SMF) for use as a kerr medium for nonlinear polarization rotation of pulses, a wavelength division multiplexer And an optical coupler for the resonator output stage.

[0070] The resonator may be a soliton laser whose entire dispersion of the resonator is a negative region or a soliton laser having a total dispersion of 0 (zero), by adjusting the length of the rare-earth doped optical fiber and the single mode optical fiber or by installing and adjusting a grating in the resonator. To generate a dispersion compensating soliton laser, which is a region near the center.

[0071] In addition, the resonator adjusts the length of the optical fiber constituting the resonator to adjust the repetition rate of the pulse, thereby controlling the generated pulse energy.

[0072] In addition, the non-linear polarization rotation controller adjusts the angle of the wave plates before and after the polarizing plate or the polarization beam splitter to adjust the polarization state of the pulse to induce the nonlinear polarization rotation mode lock, A mode lock is performed in the pulse width modulation mode to generate a pulse having a narrow width.

[0073] The saturable absorber also performs absorption for the resonator internal pulses and dispersed waves with lower fluence than saturation fluence, which is characteristic of the saturated absorber, and for absorptions of the pulses to proceed in the resonator The edges of the pulses are absorbed through the saturated absorber because the intensity of the light is weak and the absorber can no longer proceed inside the resonator. On the other hand, the middle portion of the pulse is strong in intensity, saturating the absorption in the saturated absorber, It serves as a nonlinear filter that can keep going inside and attenuates the peak output of the pulse while maintaining the pulse.

[0074] In addition, the saturated absorber is positioned before the gain medium after the nonlinear polarization rotation regulator, and at a condition where the fluence of the narrow width pulse generated by the nonlinear polarization rotation is lower than the saturation fluorescence of the saturated absorber, Because of the attenuation of the pulses and the elimination of optical noise, a single high-power femtosecond pulse is generated without generating multiple pulses by wave breaking and noise pulse amplification due to excess nonlinear effects of the pulses during amplification in the gain medium.

[0075] In addition, the saturated absorber attenuates the dispersed wave to increase the energy concentration on the main pulse.

[0076] In addition, the saturated absorber has a relaxation time that is slower than the pulse width generated by the laser, thereby facilitating initial pulse generation.

[0077] The hybrid resonator according to the present invention has the advantage of generating a high-power femtosecond pulse having a high energy concentration and an optical comb of a wide wavelength band with high stability, and can simplify the device, thereby providing an economical femtosecond laser resonator There is an effect that it can be manufactured, and there are characteristics that can be applied to various industrial fields.

[0078] While the present invention has been particularly shown and described with reference to exemplary embodiments thereof, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. On the contrary, those skilled in the art will appreciate that many modifications and variations of the present invention are possible without departing from the spirit and scope of the appended claims. And all such modifications and changes as fall within the scope of the present invention are therefore to be regarded as being within the scope of the present invention.

[0079] 10 The present invention relates to a polarizing beam splitter and a polarizing beam splitter which are used in a polarizing beam splitter and a polarizing beam splitter,) 108: wavelength division multiplexer 109: laser diode 110: rare earth doped optical fiber 111: single mode optical fiber 112: fiber isolator 200: spectrum of hybrid mode locked laser 201: auto correlation of hybrid mode locked laser 300 : Nonlinear Polarization Rotation Supremacy Mode Locked Laser Spectrum 301: Nonlinear Polarization Rotation Supremacy Mode Locked Laser Autocorrelation Signal 400: Accumulated Pulse Energy Comparison Graph 401: Accumulated Pulse Energy Percentage Comparison Graph 500: RF Spectrum of Pulse Repetition Rate 501 : Stabilized repetition rate over time frequency change graph 600: polarizer 601: optocoupler 602: optical fiber output Optical fiber based polarizer 800: volume type saturable absorber mode locking portion 1801: reflective type saturable absorber 802: fiber circulator 900: optical fiber based polarizer 800: optical fiber based polarizer 800: optical fiber based nonlinear polarization rotating mode lock portion 701: Nonlinear polarized rotation mode lock portion 901: volume type saturable absorber mode lock portion 2902:? / 4 wave plate 1000: volume isolator 1001: beam splitter 1002: diffraction grating 1003:

Claims

1. An optical fiber femtosecond laser resonator, comprising: a fiber-based resonator of a ring-type structure including a laser source, the non-linear polarization rotation mode being configured on the resonator and generating an ultrashort pulse in pulse shaping; A locking portion; And a saturable absorber mode locking unit for performing nonlinear filtering of the pulse amplitude and suppressing excess nonlinear phenomena in the resonator, generating initial pulses, and removing parasitic dispersion waves generated in the soliton pulse, And the nonlinear polarization rotation mode lock unit comprises a light port, a polarization controller, a polarization beam splitter (PBS), a polarization controller, and an optical port in this order, wherein the polarization controller is a nonlinear polarization rotation And the saturable absorber mode locking portion is formed in the order of an optical connector, a transmissive saturating wet body, and an optical connector, wherein the resonator is configured to perform nonlinear polarization rotation of the pulse Single mode optical fibers using a Wehrmack; rare earth doped optical fibers using a gain medium; And an isolator for generating a unidirectional pulse, wherein the diffraction grating is generated by coupling mode locking of the nonlinear polarization rotation and the saturated absorber, further comprising a diffraction grating (between the nonlinear polarization rotation mode lock and the saturable absorber mode lock) A high output optical fiber femtosecond laser resonator, which is produced by coupling mode locking of nonlinear polarization rotation and saturable absorber to realize total dispersion control of the resonator.

2. The transmission type saturated absorber according to claim 1, wherein the transmission type saturated absorber is formed by combining mode locking of a saturated absorber and nonlinear polarization rotation composed of one of a semiconductor saturable absorber, carbon nanotubes, and graphene Generated high power optical fiber femtosecond laser resonator.

3. The high output optical fiber femtosecond laser resonator according to claim 1, wherein the resonator is generated by nonlinear polarization rotation including a pulse reflected from a polarization beam splitter as a resonator output and coupling mode locking of a saturated absorber.

4. The high output optical fiber femtosecond laser resonator according to claim 1, wherein the resonator is generated by a combined mode lock of a non-linear

polarization rotation and a saturated absorber, further comprising an optical coupler for an output end.

5. The optical transmitter according to claim 1, wherein the saturable absorber mode locking unit comprises: an optical fiber circulator for transmitting a pulse to an input end; an optical port for collimating or focusing the light transmitted to the optical fiber circulator; And a reflective saturable absorber that implements nonlinear filtering of the pulses incident through the optical port. The high power optical fiber femtosecond laser resonator is produced by coupling mode locking of nonlinear polarization rotation and saturable absorber.

6. The apparatus according to claim 1, wherein the saturated absorber mode lock part is configured to receive a pulse transmitted through a polarizing beam splitter constituted in the nonlinear polarization rotation mode lock part, wherein the saturated absorber mode lock part comprises: A high power optical fiber femtosecond laser resonator produced by nonlinear polarization rotation consisting of and a saturated absorber and coupled mode locking of a saturated absorber.

FIGURESfGI

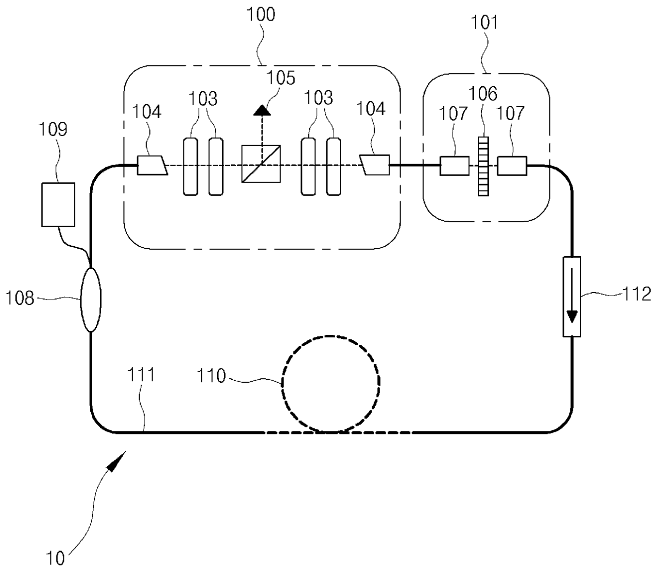
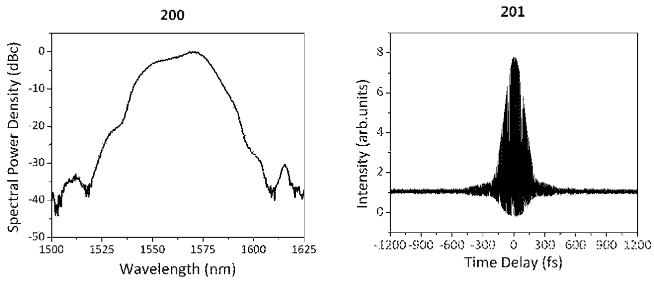
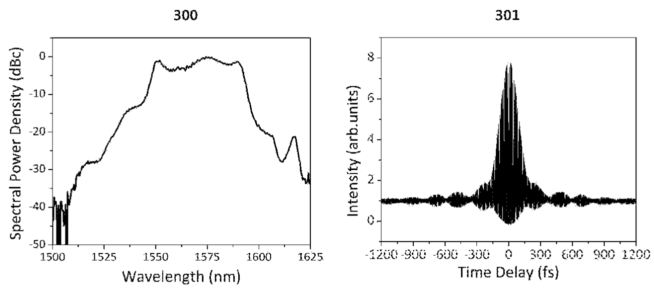


Fig. 1

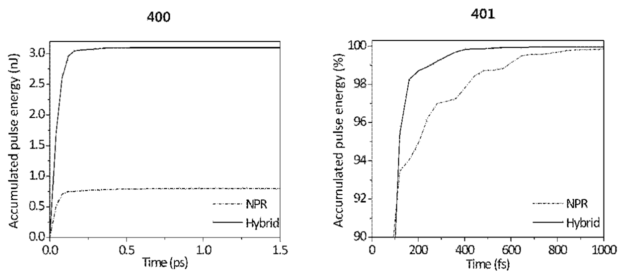
도면2



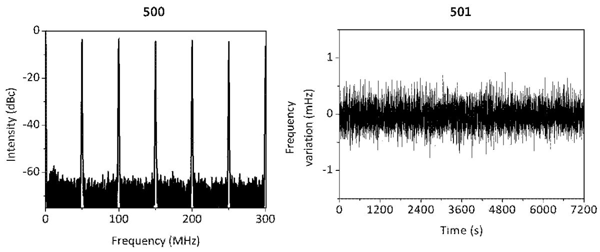
도면3



도면4



Figs., 2, 3 and 4.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-40
-60
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100
200
300
Frequency (MHz)
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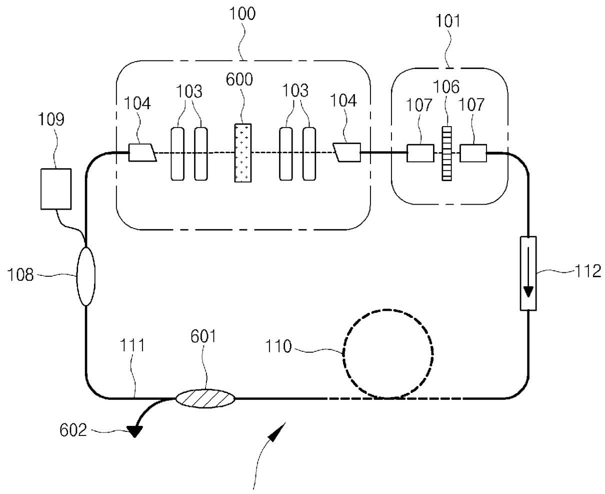
0
-1
Frequency variation (mHz)
0
1200
2400
3600
4800
6000
7200
Time (s)


100
101
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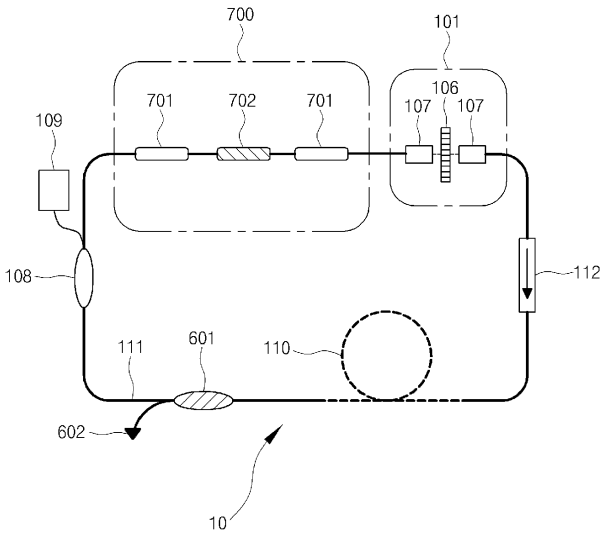
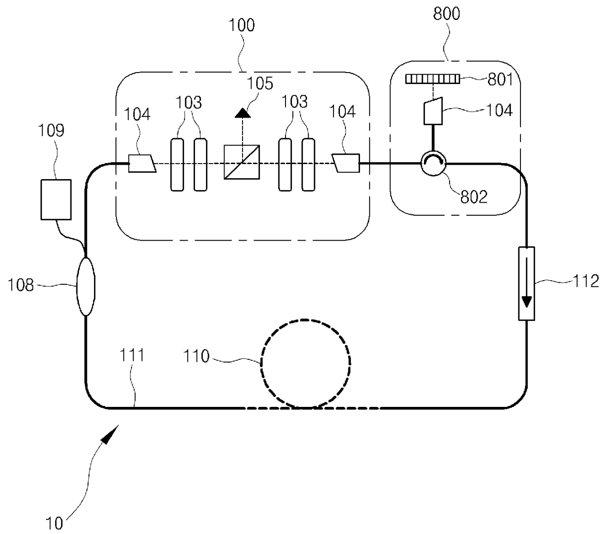
Figs., 5, 6.

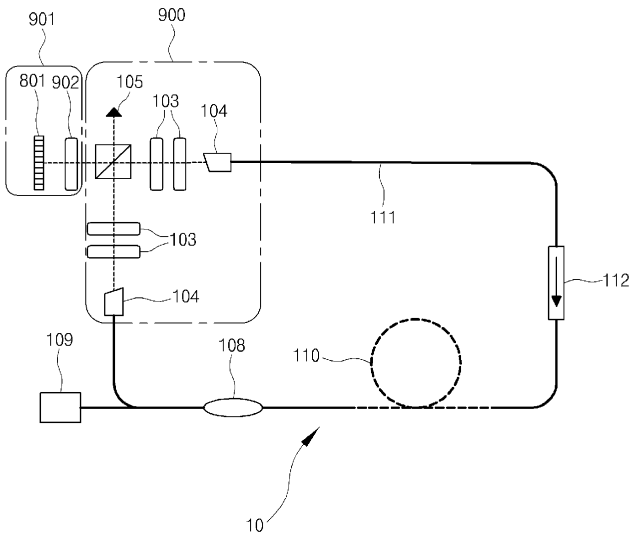
Fig



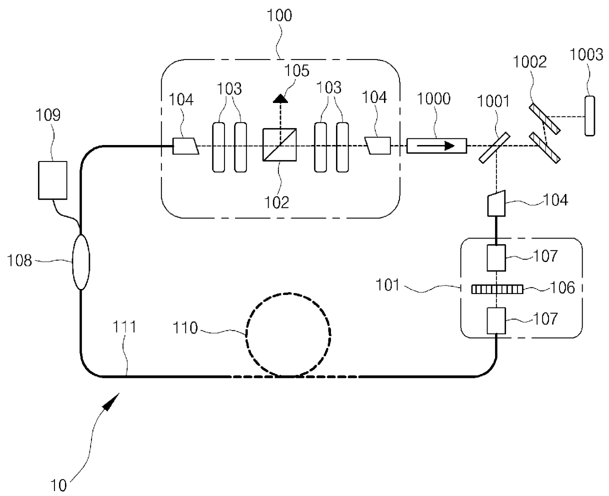
도면8



Figs., 7, 8



도면10



Figs., 9, 10

Rama Eléctrica

D02

TECHNICAL FIELD

The invention relates to the field of laser processing technology, in particular, to an all-fiber laser.

Background technique

Generally, passive mode-locked fiber laser can produce repetition rate picosecond or femtosecond pulse sequence of several MHz or tens of MHz, for example using a semiconductor saturable absorber mirror (SESAM, Semiconductorsaturableabsorbermirror), clamping or nonlinear nanotubes polarization rotation clamping. SESAM passively mode-locked fiber laser not only covers the structure of small, low price and characteristics of passively mode-locked fiber laser, is more short response time, low pump threshold value of the cavity length is not sensitive, stable performance, self-starting, cavity length is short, easy to implement high repetition frequency characteristics, thus becoming a hot topic in the field of ultrashort pulse laser.

In the Chinese patent application, Application No. Patent CN201310743241.0 "low repetition frequency of all-fiber polarization mode-locked laser" on, SESAM, polarization maintaining fiber mode field adapter, polarization maintaining single-mode fiber, polarization maintaining fiber WDM , a polarization maintaining fiber gain fiber, polarization maintaining fiber fiber grating along the optical transmission direction are connected in turn. In order to increase the surface of the incident light spot SESAM mode area, SESAM and greater than the core diameter of the optical fiber coupler 6 microns and a core diameter of greater than 6 microns and a fiber core diameter equal to about 6 microns single mode polarization maintaining fiber modulo matched field area. The patents are more cavity device, the cavity length is longer, applies only to ultrafast pulse repetition frequency of the low, and for the full polarization-maintaining fiber laser cavity must be added to the polarizer, in order to ensure output linearly polarized light. In addition, this patent gives only a theoretical diagram of the experimental program, and did not give the actual experimental results.

In the Chinese patent application, application number are CN201310743245.9 of "semiconductor has a mode field adapted saturable absorber mirror" and CN201420821818.5 of "a method for increasing the output power of the laser oscillator device" patent, in order to achieve SESAM with larger core diameter optical fiber coupling, small core diameter of single-mode polarization maintaining fiber core thermal beam expander, and then with a large core polarization maintaining optical fiber splice, reducing losses due to mode mismatch. The experiments show that the use of thermal expansion of the core to increase the beam spot incident SESAM mode field area of the package will cause the mode-locked pulse can not be self-starting. After several experiments, using the lens of the beam beam expander, increasing the SESAM in the incident beam size at the same time, the mode-locked pulses can not solve a problem from the start. However, this patent-pending laser heterodyne system during operation stability, it is difficult to shorten the cavity length of the case, to obtain a high pulse repetition rate ultrafast.

To sum up, the whole structure of a conventional fiber laser in practical use, it is clear the presence of defects and inconvenience, it is necessary to be improved.

SUMMARY

In response to these shortcomings, the utility model aims to provide an all-fiber laser, to increase the output power and stability of all-fiber laser systems, and in shortening the all-fiber laser cavity length of the case, to obtain a high repetition frequency ultrafast pulses.

In order to achieve the object of the invention, utility model, the utility model provides an all-fiber laser comprising: a semiconductor sequentially arranged saturable absorber mirror module, both from the polarizing and wavelength division multiplexing functionality integrated device bias, PM gain fiber, polarization maintaining fiber grating, as well as pump source; and the semiconductor saturable absorber mirror module and the polarization maintaining fiber grating of the two all-fiber laser mirrors.

According to the all-fiber laser, said semiconductor saturable absorber mirror module comprises: sequentially arranged semiconductor saturable absorber mirror chips, lenses and collimators.

According to the all-fiber laser, the polarizing integrated device comprising:

Elect the slow axis direction of the all-fiber laser light in the mirror transmission polarizer; and said pump source wavelength of the pump light total reflection of the signal from the optical wavelength transmission polarizer high permeability, as well as the different wavelengths of the light transmission polarizer composite membrane filters with transmission.

According to the all-fiber laser, said semiconductor saturable absorber mirror module is provided with a heat sink.

According to the all-fiber laser, said semiconductor saturable absorber mirror coating on the chip attached to the heat sink.

According to the all-fiber laser, fiber laser further comprises the full control of the semiconductor saturable absorber mirror module thermostatic temperature control systems work.

According to the all-fiber laser, the temperature control system comprises a thermoelectric cooler and its control circuit.

All-fiber laser of the present utility model provides for full polarization maintaining fiber laser, for the full polarization maintaining fiber laser cavity need to add polariser elect linearly polarized light. And the polarizer, and integrated wavelength division multiplexer, which simplifies the endovascular devices to improve system stability all-fiber lasers, and can shorten the cavity length to obtain ultra high pulse repetition frequency. Cavity length under different circumstances, by optimizing the parameters of the cavity corresponding to other devices, ultrafast pulses can be obtained a stable, low repetition frequency and high repetition rate. In addition, certain parameters of semiconductor saturable absorber mirror, select the appropriate parameters polarization maintaining fiber grating can get close to the limit transmission output beam, the beam chirp is very small, is conducive to the subsequent amplification.

BRIEF DESCRIPTION

FIG. 1 is a block diagram of the present utility model provides all-fiber laser;

Figure 2 is a schematic view of an integrated structure of the device of the present utility model provides the utility model all-fiber laser;

Figure 3 is a utility model spectra obtained ultrafast pulse of the utility model;

Figure 4 is a utility model obtained ultrafast pulse time-domain pulse waveform diagram of the utility model;

Figure 5 is a utility model diagram obtained ultrafast pulse width of the utility model.

detailed description

In order to make the utility model objects, technical solutions and advantages more clearly understood, the accompanying drawings and the following embodiments, the present utility model is further described in detail. It should be understood that the specific embodiments described herein are only used to explain the present utility model is not intended to limit the utility model.

Referring to Figure 1, in the utility model of embodiment, there is provided a 100 all-fiber laser, comprising: a semiconductor sequentially arranged saturable absorber mirror module 1, since both polarizing and wavelength division multiplexing function of partial integration device 2, 3 polarization maintaining gain fiber, polarization maintaining fiber grating 4, 5 and pumping source; and the semiconductor saturable absorber mirror module 1 of the polarization maintaining fiber grating 4 constituting the semiconductor all-fiber laser 100 and two mirrors. Figure 1 also shows an all-fiber laser optical path 100.

In this embodiment, includes a semiconductor saturable absorber mirror module 1, the polarizer integrated device 2, PM 3 gain fiber, polarization maintaining fiber grating 4 and 5 pumping source. Wherein the semiconductor saturable absorber mirror module 1 polarization maintaining fiber grating 4 respectively constituting the two fiber lasers and mirrors. Semiconductor saturable absorber mirror module 1 includes a semiconductor saturable absorber mirror chip 6, 7 and collimator lens 8. Transfer chamber, a thin film filters 10 in the optical pump light polarizer integrated device 2 shown in Figure 2, it will be from 10 integrated filters 9 and polarizer film, polarizer 9 selected slow axis all-trans wavelength of the signal light wavelengths of high permeability, it is the synthesis of light with different wavelengths for transmission, so that the integrated device 2 also has a polarizing and wavelength division multiplexing function.

In the utility model of embodiment, a semiconductor saturable absorber mirror module 1 may increase the incident beam mode field area of the semiconductor chip 5 saturable absorber mirror surface of the semiconductor saturable absorber mirror under certain saturation flux threshold value, the semiconductor saturable absorption mirror stable clamping required average power increases, which increases the ultrafast fiber laser output power. Semiconductor saturable absorber mirror module 1 components used have little effect on polarization can be achieved from the start.

In the utility model of embodiment, a semiconductor saturable absorber mirror module 1 comprising: sequentially arranged semiconductor saturable absorber mirror chip 6, 7 and collimator lens 8. Partial sky 2 integrated device comprising:

Elect the slow axis direction of the all-fiber laser light in the mirror transmission polarizer 9; and

Said pump light wavelength pumping source 5 all-trans, as a signal of the optical wavelength transmission polarizer high permeability, and the synthesis of different wavelengths of light from the polariser 9 transmitted with transmission film filters 10.

Preferably, the semiconductor saturable absorber mirror module set 1 has fins. The semiconductor saturable absorber mirror chip cover 6 on the heat radiation member. In addition, all-fiber laser 100 also includes control of the semiconductor saturable absorber mirror module 1 thermostatic temperature control systems work. The temperature control system includes a thermoelectric cooler and its control circuit.

Since the semiconductor saturable absorber mirror to heat very sensitive semiconductor saturable absorber mirror module 1 contains a heat sink, wherein the semiconductor saturable absorber mirror chip 6 on the heat sink, so that the semiconductor saturable absorber mirror full cooling, stable optical performance, pulse output also will be stable. In order to improve the sensitivity of the product weaken the environmental temperature change, the semiconductor saturable absorber mirror module 1 plus the temperature control system. The temperature control system includes a thermoelectric cooler (TEC, ThermoelectricCooler) and its control circuit, when the ambient temperature changes, to ensure that the semiconductor saturable absorber mirror module temperature 1 maintained at a certain temperature range unchanged, namely to ensure that the semiconductor saturable absorber mirror constant operating temperature and improve overall system sensitivity to temperature resistance.

Spectral curve all-fiber laser provides the utility model has been very smooth, no glitches; pulse sequence rates are balanced, and the pulse width can be as low 10ps or less.

In summary, all-fiber laser of the present utility model provides for full polarization maintaining fiber laser, for the full polarization maintaining fiber laser cavity need to add polariser elect linearly polarized light. And the polarizer, and integrated wavelength division multiplexer, which simplifies the endovascular devices to improve system stability all-fiber lasers, and can shorten the cavity length to obtain ultra high pulse repetition frequency. Cavity length under different circumstances, by optimizing the parameters of the cavity corresponding to other devices, ultrafast pulses can be obtained a stable, low repetition frequency and high repetition rate. In addition, certain parameters of semiconductor saturable absorber mirror, select the appropriate parameters polarization maintaining fiber grating can get close to the limit transmission output beam, the beam chirp is very small, is conducive to the subsequent amplification.

Of course, the utility model may also have other various embodiments, without departing from the spirit and essence of the utility model case, those skilled in the art as corresponding to various changes and modifications may be made in accordance with the present utility model, but these should be the appropriate changes and modifications within the scope of protection of the utility model appended claims.

CLAIMS

1.An all-fiber laser, characterized by comprising: a semiconductor sequentially arranged saturable absorber mirror module, both from the polarizing and wavelength division multiplexing functionality integrated device partial polarization maintaining gain fiber, polarization maintaining fiber grating, and pump source; and the semiconductor saturable absorber mirror module and the polarization maintaining fiber grating of the two all-fiber laser mirrors.

2.According to claim 1, wherein the all-fiber laser, wherein said semiconductor saturable absorber mirror module comprises: sequentially arranged semiconductor saturable absorber mirror chips, lenses and collimators.

3.According to an all-fiber laser according to claim, characterized in that said polarizing integrated device comprising:

Elect the slow axis direction of the all-fiber laser light in the mirror transmission polarizer; and

Said pump source wavelength of the pump light total reflection of the signal from the optical wavelength transmission polarizer high permeability, as well as the different wavelengths of the light transmission polarizer composite membrane filters with transmission.

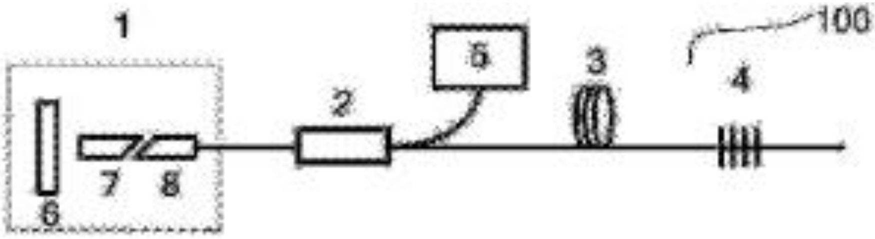
4.According to claim 2, wherein the all-fiber laser, wherein said semiconductor saturable absorber mirror module is provided with a heat sink.

5.All-fiber laser according to claim 4, wherein said semiconductor saturable absorber mirror coating on the chip attached to the heat sink.

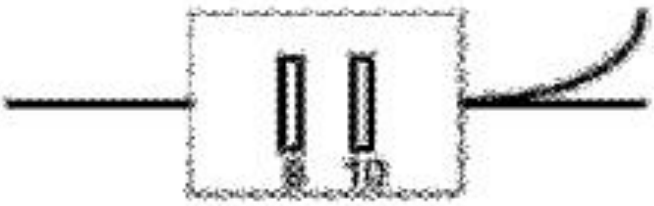
6.All-fiber laser according to claim 2, wherein said full control of the fiber laser further comprises a semiconductor saturable absorber mirror module thermostatic temperature control systems work.

7.All-fiber laser according to claim 6, wherein the temperature control system comprises a thermoelectric cooler and its control circuit.

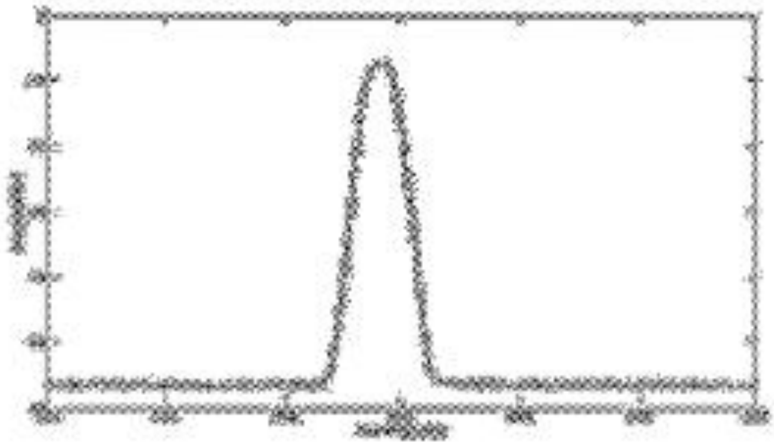
FIGURES



제 1



제 2



제 3

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Harmonic Order-Dependent Pulsewidth Shortening of a Passively Mode-Locked Fiber Laser With a Carbon Nanotube Saturable Absorber

Volume 4, Number 5, October 2012

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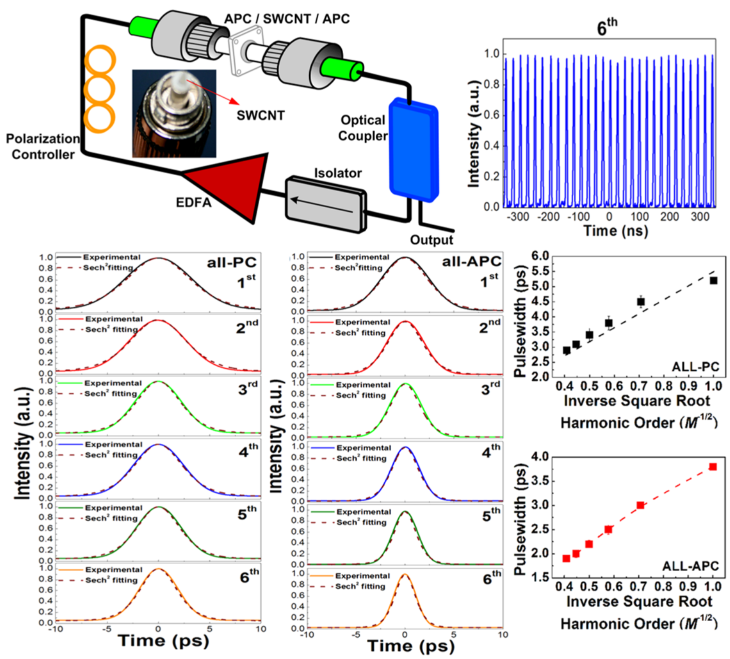

DOI: 10.1109/JPHOT.2012.2210398
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Harmonic Order-Dependent Pulsewidth Shortening of a Passively Mode-Locked Fiber Laser With a Carbon Nanotube Saturable Absorber

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DOI: 10.1109/JPHOT.2012.2210398

Manuscript received July 14, 2012; accepted July 21, 2012. Date of publication July 31, 2012; date of current version August 16, 2012. This work was partially supported by the National Science Council, Taiwan, under Grants NSC98-2221-E-002-023-MY3, NSC99-2622-E-002-024-CC2, and NSC101-2622-E-002-009-CC2. Corresponding author: G.-R. Lin (e-mail: grlin@ntu.edu.tw).

Abstract: A pumping-power-dependent high-order harmonic mode-locking erbium-doped fiber laser (HML-EDFL) with a single-wall carbon nanotube (SWCNT)-doped polyvinyl alcohol (PVA)-based saturable absorber is investigated. The HML-EDFL systems using either all-physical-contact (PC) or all-angled-physical-contact (APC) connectors examined in this study show stably mode-locked pulse trains; however, the all-PC connector-based system requires a larger pumping power to initiate the mode-locking and generate a broader pulsewidth of 2.9–5.2 ps at same HML order. The all-APC connector-based HML-EDFL system can provide pulsewidth shortening from 3.8 to 1.9 ps associated with a spectral linewidth broadened from 0.7 to 1.36 nm by increasing the HML order from first to sixth. Either the all-PC or the all-APC connector-based EDFLs can deliver a nearly transform-limited pulse with a time–bandwidth product (TBP) of 0.32. The EDFL passively mode-locked by SWCNT-doped PVA delivers a pulse train with a signal-to-noise ratio (SNR) remaining higher than 40 dB for different HML orders, whereas the side-mode suppression ratio (SMSR) lower than 32 dB inevitably introduces an unequalized peak amplitude phenomenon for adjacent pulses at higher HML operations. A modified Haus' master equation is derived to explain the inverse proportionality of the passive HML-EDFL pulsewidth to the square root of HML order, which is correlated with the shortened carrier recombination time of the SWCNT saturable absorber at higher pumping power or circulating pulse intensity.

Index Terms: Carbon nanotubes and confined systems, mode-locked lasers, erbium lasers, fiber lasers.

1. Introduction

Passive mode-locking of erbium (Er)-doped fiber laser (EDFL) and ytterbium (Yb)-doped fiber lasers that generate self-started picosecond pulses by using single-wall carbon nanotube (SWCNT)-based saturable absorbers has been demonstrated in the past few years [1]–[9]. In 2004, Set *et al.* demonstrated an SWCNT-based saturable absorber for suppressing the intensity noise of ultrafast optical pulses in the picosecond regime [1]. By incorporating an SWCNT saturable absorber, Yamashita *et al.* also demonstrated the passive mode-locking of a 2-cm-long Er and Yb co-doped fiber Fabry–Pérot laser with a pulsewidth of 680 fs at a repetition rate of 5 GHz [3]. Subsequently, Martinez and Yamashita also demonstrated a linear-cavity passively mode-locked EDFL with a fundamental repetition rate of up to 19.45 GHz [4]. Recently, Chiu *et al.* have employed an SWCNT-doped polymer film to investigate the effects of concentration and thickness of the SWCNT-doped polymer film on starting the passive mode-locking and on shortening the EDFL pulses [8], [9]. Until recently, most works were focused on mode-locking the EDFLs at a fundamental frequency (decided by longitudinal mode spacing) using SWCNT-based saturable absorbers, whereas the harmonic mode-locking (HML) capability of the SWCNT-based saturable absorbers was seldom discussed. A 23rd-order passive HML of the EDFL with a pulsewidth of 1.3 ps was experimentally observed at a central wavelength of 1530 nm [10]. In addition, the adjustment of the repetition rate of a passively mode-locked fiber laser was proposed by using a delayed optical path scheme. The phenomenon of a passive HML-EDFL with 500-fs pulsewidth at a harmonic frequency of 2 GHz using a nonlinear amplifier loop mirror (NALM) and a multiple-quantum-well saturable absorber was demonstrated as early as 1997 [11]. Alternatively, a passive HML-EDFL based on nonlinear polarization rotation (NPR) at harmonic repetition frequency of up to 1.2 GHz has been reported [12]. In a theoretical analysis, Kutz and Sandstede characterized the nonlinear mode coupling (NLMC) behavior in a waveguide array to explain the HML mechanism [13]. An ML/HML switchable EDFL, with its pulsewidth varying at different HML orders, was also demonstrated by different pumping powers. Either the ML or the HML can be initiated with a semiconductor saturable absorber mirror (SESAM) and adjusted by controlling the intracavity polarization [14].

The HML technique has been frequently used in actively modulated EDFL systems but has been seldom observed and discussed in the passively mode-locked EDFL systems. The reason is that the HML technique is hard to control in such passively mode-locked lasers that are started with inherent saturable absorbers. Nevertheless, the passive HML of EDFL is still worthy of a detailed investigation because passive mode-locking can provide a shorter pulsewidth than active mode-locking, and the higher HML order can enable a passive HML-EDFL to deliver a pulse train with repetition frequency as high as an active HML-EDFL. More specifically, the establishment of a theoretical HML model is required to understand the correlation between the pulsewidth and the HML order in a passive HML-EDFL system. In this paper, the use of intracavity polarization adjustment in the passive HML-EDFL systems with either physical-contact (PC) or angled-physical-contact (APC) connectors is demonstrated and compared. The performances of the EDFL with variable HML from first to sixth order by using an SWCNT-doped polyvinyl alcohol (PVA) film as a fast saturable absorber are characterized. The HML performances of the EDFL systems using either all-PC or all-APC connectors are analyzed and compared. Except for the absorption and propagation losses of the EDFL cavity, all of the connectors between adjacent patchcords also contribute an additional loss in the EDFL cavity that limits the pulsewidth shortening. Using APC connectors can reduce the interfacial reflection to decrease the connection loss, thus enabling a shortened laser pulsewidth to be produced from the passively mode-locked EDFL cavity. The strong competition between the fundamental and the harmonic frequency components under high-order HML operation is observed and elucidated. In addition, the correlation between the HML-EDFL pulsewidth and the HML order is derived from the modified Haus' master equation. The pulsewidth of the passive HML-EDFL is observed to be shortened with increasing HML order.

2. Experimental Setup

The passive HML-EDFL system with an intracavity SWCNT-doped PVA film is illustrated in Fig. 1(a). The total cavity length of the EDFL is approximately 28.5 m, which consists of a 980/1550-nm wavelength-division multiplexing (WDM) coupler for launching the 980-nm pumping laser into the EDFL cavity, an isolator to control the direction of light circulating in the EDFL fiber ring, a polarization controller (PC) for adjusting the HML order, a 90/10 output coupler (OC), and the SWCNT-doped PVA-film-based saturable absorber inserted between either the FC/PC- or the FC/APC-type ferrule connectors. The remainder of the EDFL ring cavity consists of a single-mode fiber (SMF, Corning SMF-28). The group velocity delay (GVD) parameters of SMFs and Er-doped fibers (EDFs) are

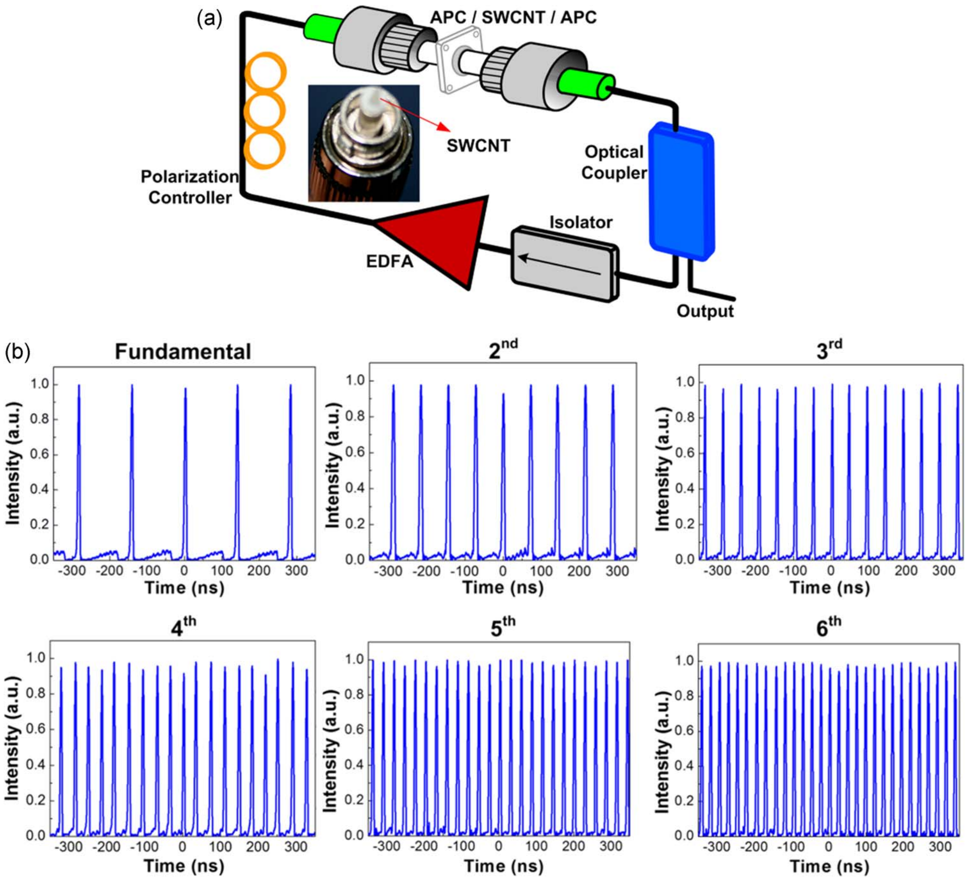

Fig. 1. (a) The configuration of the passive HML-EDFL system. Inset shows the fiber connector with the SWCNT-doped PVA film. (b) The variations of HML order of mode-locking EDFL with different pumping powers.

approximately estimated to calculate the net group delay dispersion (GDD) in the passive HML-EDFL cavity [15]. The only different parameter between the all-PC and the all-APC constructed EDFL architectures is the type of connector used in the EDFL cavity. All of the cavity parameters, including GVD, cavity length, and coupling ratio, remain unchanged for both of the passive HML-EDFL systems with all-PC and all-APC connectors.

All of the fiber-based components are packaged in a cylindrical stainless steel case to ensure the robustness of the entire system. The stainless package is isolated from other circuitry and current sources to prevent the system from thermal and electromagnetic influences. Only the screw of the PC is accessible to adjust the HML order during the experiment. The intracavity polarization plays an important role to obtain stabilized HML [14]. A programmable controlled PC is inserted to record the polarization change for different HML orders quantitatively. The optimized HML varying from fundamental to the sixth order is achieved by further increasing the pumping power from 45 to 100 mW [see Fig. 1(b)]. The pulsewidth, pulse train, and spectra linewidth of the passive HML-EDFL setups with either all-PC or all-APC connectors are characterized by an autocorrelator (Femtochrome, FX-103L), a sampling oscilloscope (Agilent 86100A), an optical spectrum analyzer (Ando, AQ-6317B), and an RF spectrum analyzer (Agilent 8565E).

3. Results and Discussion

Fig. 2(a) and (b) shows the nonlinear transmittance and nonlinear absorption of the SWCNT-doped PVA film used as a saturable absorber. A pulsed laser with duration of 700 fs at central wavelength

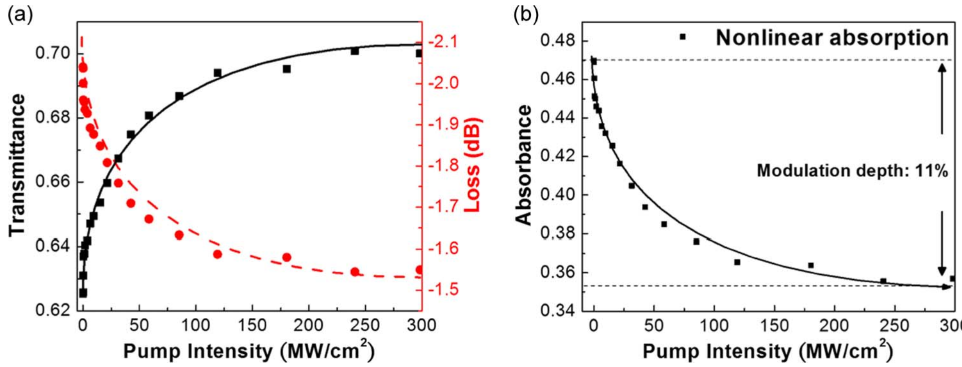

Fig. 2. (a) The nonlinear transmittance and corresponding loss and (b) the nonlinear absorption of the SWCNT-doped PVA film used for the passive HML-EDFL systems.

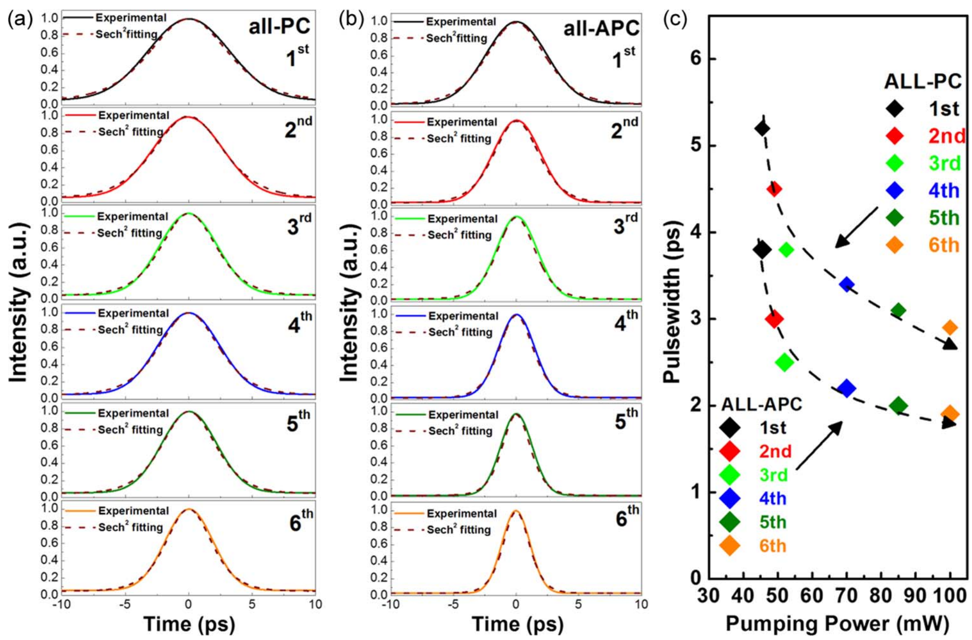

Fig. 3. Autocorrelation traces of the passive HML-EDFL with (a) all-PC and (b) all-APC connector systems. (c) The variations of pulsewidth with all-PC and all-APC systems versus pumping power.

of 1560 nm is employed as the pumping source. The transmittance of the SWCNT-doped PVA film increases from 0.625 to 0.7 as the pumping intensity increases from 0.3 to 300 MW/cm^2. The linear (i.e., nonsaturable) loss of the SWCNT-doped PVA film measured by using a continuous-wave laser source at same wavelength is -2.2 dB at a pumping power of 1 mW. According to the high-power pulsed laser analysis, the absorbance of the SWCNT-doped PVA film is saturated at 0.47, corresponding to a saturable loss as small as -1.5 dB. The modulation depth is up to 11%, as shown in Fig. 2(b).

In the all-PC connector-based system, the higher HML order can be easily obtained by increasing the pumping power and by slightly adjusting the intracavity polarization. Fig. 3 shows the autocorrelated pulse shapes of the fundamental, second-, third-, fourth-, fifth-, and sixth-order HML under a pumping power of 45.5, 49, 52.5, 70, 85, and 100 mW, respectively. Due to the design of a completely dispersion-compensated cavity, the EDFL with an intracavity all-PC connector scheme

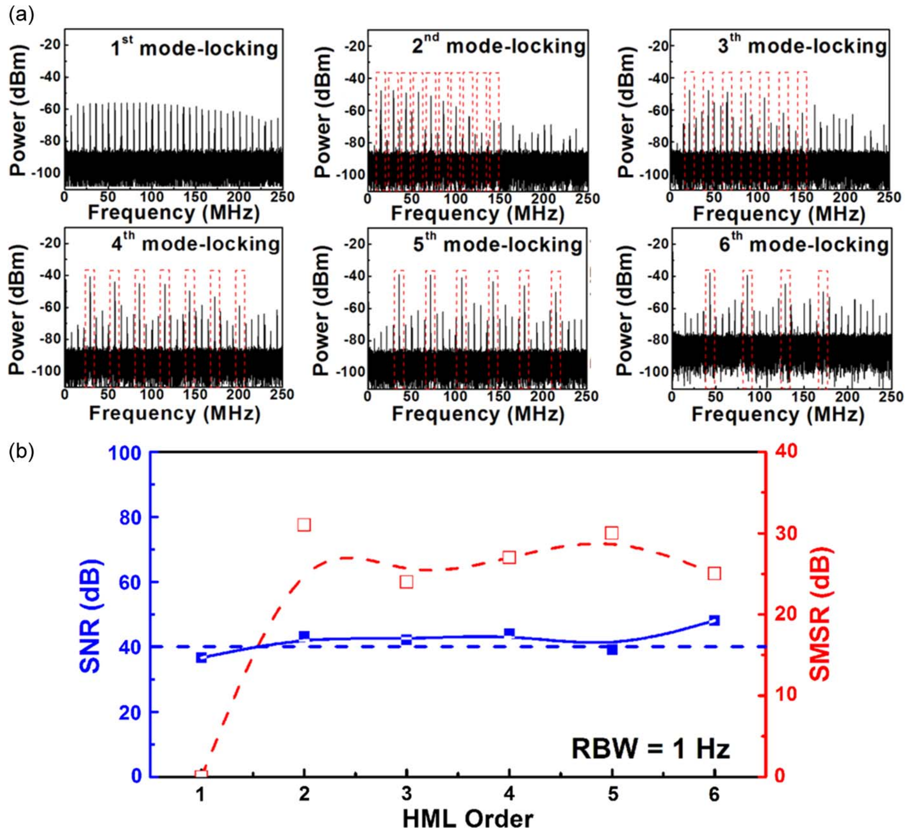

Fig. 4. (a) RF spectra of the passive HML-EDFL. (b) The SNR and SMSR of the passive HML-EDFL pulse at different HML orders.

can still operate under passive HML to deliver a pulse that can be perfectly fitted by a hyperbolic secant function. However, the effective cavity gain in this all-PC connector system is not sufficient to produce a short pulse; only a modest pulsewidth shortening is provided from 5.2 to 2.9 ps by increasing the HML order, as shown in Fig. 3(a). By changing all of the intracavity patchcords from PC to APC connectors to reduce the interfacial reflection, a significantly shortened HML pulsewidth can be obtained from the all-APC connector-based EDFL system [see Fig. 3(b)]. Reducing the interfacial reflection can decrease the cavity loss, which enhances the intracavity gain and the circulating power because the pulsewidth of the passively mode-locked EDFL is inversely proportional to the square root of the intracavity power [16], as shown in

$$\tau^2 = \frac{2D_g}{\gamma|A|^2} \tag{1}$$

where D_g is the gain dispersion, and γ and A are the modulation depth and the wave amplitude, respectively. Therefore, a narrower pulsewidth can be obtained by using the all-APC connector system. In comparison to the all-APC connector-based scheme, the all-PC connector-based scheme requires a higher threshold pumping power to provide the passive HML-EDFL. This result is mainly attributed to the additional loss caused by the end-face reflections of the all-PC connectors, which inevitably leads to a smaller effective cavity gain for the passive HML-EDFL. As a result, the insufficient gain leads to a broadened pulse with reduced spectral linewidth.

Fig. 4(a) shows the optoelectronic-converted HML spectra involving different harmonic frequency compositions for the all-APC connector-based EDFL at different HML orders. With the same frequency ranging from 0 to 250 MHz, the dominated HML frequency component group increases

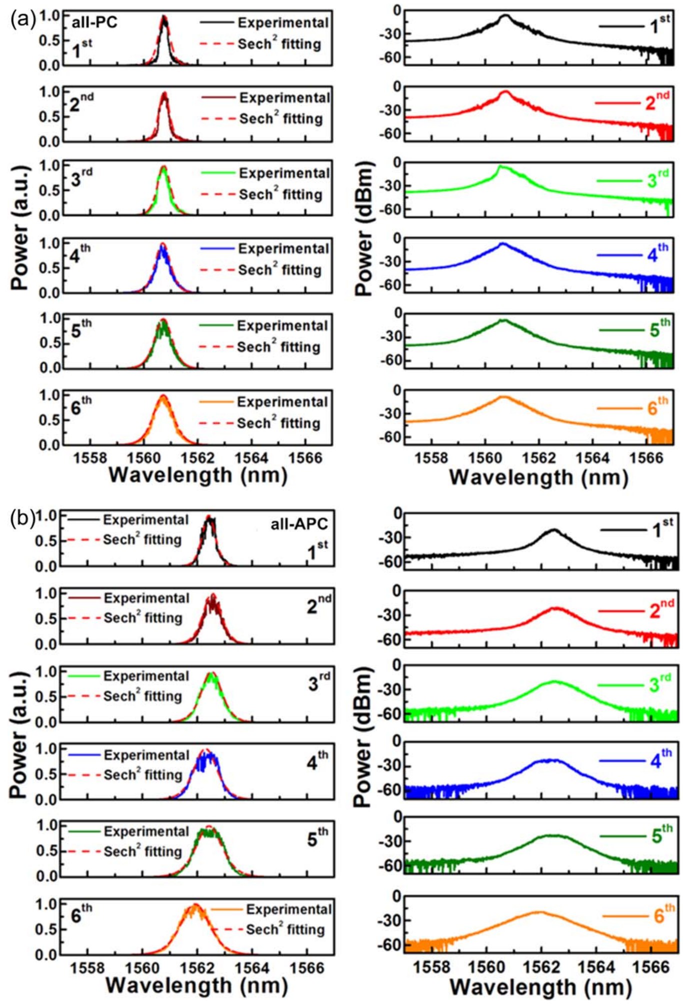

Fig. 5. (a) The spectra of the passive HML-EDFL with all-PC connector; left: *y*-axis in linear scale, right: *y*-axis in log scale. (b) The spectra of the passive HML-EDFL with all-APC connector; left: *y*-axis in linear scale, right: *y*-axis in log scale.

its spacing from 7 to 42 MHz with increasing HML order. The side-mode suppression ratio (SMSR) in the RF power spectrum is defined as the stationary (time-averaged) RF peak power ratio of the principle mode to the second most dominant side mode, as given by $\mathrm{SMSR_{dB}} = 10\log(\overline{P_P}/\overline{P_{P'}}) = \overline{P_{P,\,dB}} - \overline{P_{P',\,dB}}$, where $\overline{P_P}$ and $\overline{P_{P'}}$ represent the RF peak powers of the desired HML frequency component and the second largest frequency component at other harmonics. The SMSR shows distinct enhancement at lower HML orders; however, a degraded SMSR of the higher HML frequency component is also observed. In addition, the signal-to-noise ratio (SNR) of the HML frequency component to the noise background mode-locked EDFL system is analyzed to characterize the mode-locking quality, which is defined as $\mathrm{SNR_{dB}} = 10\log(P_{signal}/P_{noise}) = P_{signal,dB} - P_{noise,dB}$, with P_{signal} and P_{noise} denoting the RF peak powers of the desired harmonic signal and the noise background, respectively. The SNR remains nearly constant at $\sim$40 dB, whereas the largest SMSR at each HML condition is gradually saturated at 25–32 dB due to the competition between the harmonic and the fundamental mode-locking mechanisms [see Fig. 4(b)]. The total length of the SMF with a GVD parameter β_2 of $-20\ \mathrm{ps^2/km}$ used in the EDFL cavity is 16 m [15]. The length of the EDF with β_2 of 17 $\mathrm{ps^2/km}$ used in the EDFL cavity is 12.5 m. After calculation, the residual GDD parameter is only $-0.1\ \mathrm{ps^2}$, and the EDFL cavity is in the anomalous dispersion regime. A long EDFL cavity without precise temperature and environmental control

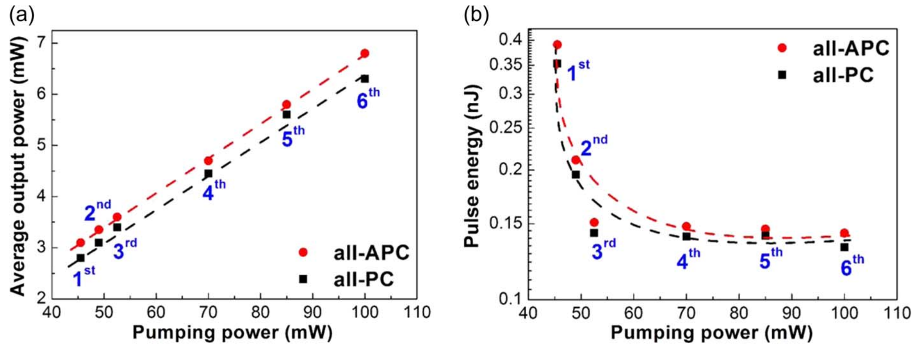

Fig. 6. (a) Average output power versus pumping power for both the all-PC and all-APC connector systems. (b) Output pulse energy versus pumping power for both the all-PC and all-APC connector systems.

inevitably introduces unwanted fluctuations, so the HML pulse train could become unstable for a long-cavity case. Therefore, the higher order HML is possible with a better management of the cavity dispersion, the cavity length, and the feedback control.

Note that the different HML orders can also be adjusted by changing the pumping power in the all-APC EDFL system, and a pumping power lower than that required for the all-PC EDFL system (45–100 mW for first- to sixth-order HML) is observed. In comparison to the all-PC connector system, the all-APC connector system requires less pumping power to launch the HML at different orders. A comparison of the autocorrelated traces from both systems reveals that the output of the passive HML-EDFL is more stable in the all-APC connector system because the dc level and the intensity fluctuation of the autocorrelated pulse traces obtained from the passive HML-EDFL cavity is greatly suppressed [see Fig. 3(a) and (b)]. Simultaneously, the intensity fluctuation of the SWCNT-doped PVA passively mode-locked EDFL pulse train is monitored using a digital sampling oscilloscope (Agilent 86100A with 86106B plug-in module). The output of HML in the all-APC connector-based EDFL system exhibits improved stability over that in the all-PC connector-based EDFL system. The switching of HML order strongly depends on the pumping power, and the generation of a higher HML order pulse train usually requires a larger pumping power. The entire system is still operated in a self-amplitude modulation regime because the Kelly sideband spectrum is not observed [17]. Nevertheless, the pulse is significantly shortened by changing the connectors from PC to APC, thus providing pulsewidths in the range of 1.9–3.8 ps by using the all-APC connector-based EDFL system, as shown in Fig. 3(c).

The all-APC connector-based EDFL delivers a shorter pulsewidth because it reduces unwanted intracavity reflection from adding to the cavity loss of the EDFL, thereby increasing the effective intracavity gain $(g' = g - L)$ to further shorten the mode-locked pulsewidth. Fig. 5(a) shows that the spectral linewidth of the HML pulse in the all-PC connector system ranges from 0.5 to 0.93 nm, whereas the spectral linewidth of the HML pulse from the all-APC connector-based EDFL is broadened from 0.7 to 1.36 nm, as shown in Fig. 5(b). Obviously, the amplified spontaneous emission (ASE) of the all-PC spectrum is larger than that of the all-APC spectrum due to the lower mode-locking strength. Due to a lower pulse-shortening force, the residual ASE component in the spectra output from the all-PC connector-based system is much broader than those from the all-APC connector-based system, as shown in Fig. 5. This result can also be treated as a direct evidence for the incomplete mode-locking of the all-PC connector-based EDFL system. Fig. 6(a) shows the average output power versus the pumping power for both the all-PC and all-APC connector systems. The pulse energy shown in Fig. 6(b) is simply calculated by $E_p = P_{pk}\tau_p = cTP_{ave}$, with P_{ave} denoting the average output power, P_{pk} denoting the peak power, $c = 0.8814$ for a sech^2 pulse, and T and τ_p as the pulse repetition period and the pulsewidth, respectively [18].

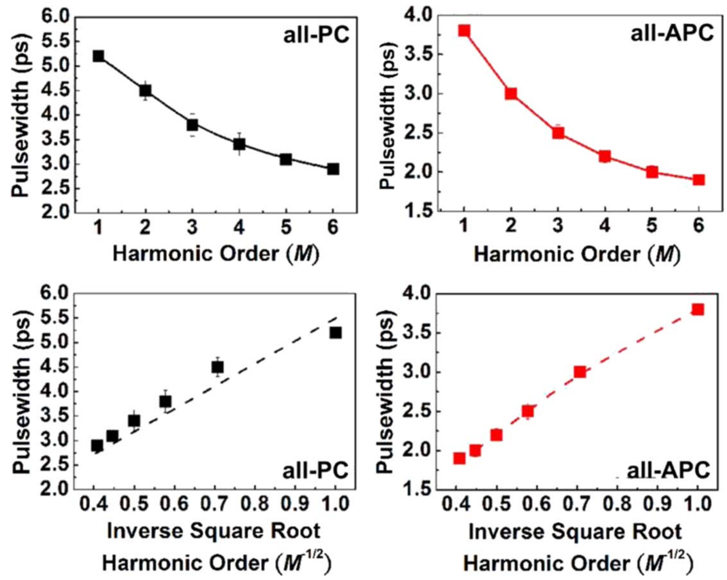

Fig. 7. Relationship between pulsewidth and HML order of all-PC and all-APC connector-based EDFL systems.

Fig. 7 shows the relationship between the pulsewidth and the HML order for the EDFL with all-PC and all-APC connector-based configurations. The pulsewidth in the all-PC connector-based system is shortened from 5.2 to 2.9 ps and that in the all-APC connector system is shortened from 3.8 to 1.9 ps, with the HML order increasing from first to sixth. More specifically, the HML phenomenon observed in the passively mode-locked EDFL is quite similar to that observed in the actively mode-locked system, where the multiple-period fast saturable absorption effect of the SWCNT occurring within one period is thought to play an important role. In other words, the pumping-power-dependent HML order indicates that the absorption of SWCNT may be saturated and recovered for several times if the pumping power is sufficiently large to support the gain of the intracavity circulated HML pulse. One piece of evidence for this saturation behavior is that the equation for the carrier recombination time can be given by $\tau = \hbar N\omega/\alpha I$ [19], where N denotes the saturable carrier density, ω represents the frequency of light, α is the nonlinear saturable absorption coefficient, and $\hbar$ is the reduced Planck's constant. At the same saturable carrier density, there is an inverse relationship between the carrier recombination time and the intracavity pulse intensity. However, this equation is only valid for the results obtained under continuous-wave or long-pulse excitation. To clarify, Haus' master equation for the passively mode-locked lasers is subsequently used to derive the proper relationship between the shortened pulsewidth and the HML order. Therefore, the modulation coefficient γ employed to describe the saturable absorption needs to be modified by a periodically changed one during such an HML process, and the modeling work using a modified Haus' master equation is necessary to provide a proper result.

The solution of such an HML pulse derived from the modified Haus' master equation is compared with the one established for the active mode-locking case. In principle, the HML pulsewidth of an active HML laser system reveals a proportionality to the fourth root of gain and is inversely proportional to the square root of the modulating frequency and the modulation coefficient. The actively mode-locked pulsewidth shortening with increasing HML order [20] can be theoretically modeled to yield an empirical formula of $\tau_p = (2\ln 2/\pi^2)^{1/2}[(2g_0/\partial^2)^{1/4}/(f_m\Delta\nu)^{1/2}]$, where τ_p is the pulsewidth, g_0 is the single-pass integrated gain, f_m is the modulation frequency, δ is the modulation depth, and $\Delta\nu$ is the homogeneous linewidth. In principle, the active HML pulsewidth of the mode-locking pulse is inversely proportional to the square root of the HML order M times of the fundamental frequency [21]. In the passive HML case without group-velocity dispersion and self-phase modulation, the pulse train exhibits a repetition time defined as one Mth of its round-trip time (T_R), and the solution of the modified Haus' master equation shown below is still a hyperbolic secant function [16],

$$\begin{aligned}\frac{T_R}{M}\frac{\partial A(T,t)}{\partial \mathrm{T}} &= \left[-l + j\sum_{n=2}^{\infty} D_n\left(j\frac{\partial}{\partial t}\right)^n + g(T)\left(1 + D_g\frac{\partial^2}{\partial t^2}\right) - q(T,t) - j\delta|A(T,t)|^2\right]A(T,t)\\ &= \left[g - l + D_g\frac{\partial^2}{\partial t^2} - \left(q_0 - \gamma|A|^2\right)\right]A(T,t)\\ &= \left[g - l_0 + D_g\frac{\partial^2}{\partial t^2} + \gamma|A|^2\right]A(T,t)\end{aligned} \quad (2)$$

where $A(T,t)$ denotes the field function, l is the EDFL cavity loss, D_n is the nth-order dispersion, $g(T)$ is the EDFL gain, D_g is the gain dispersion, $q(T,t)$ is the saturable absorption of the SWCNT, and $\partial|A|^2$ is the self-phase modulation term. By utilizing the solution of $A(T,t) = A_0\mathrm{sech}(t/\tau_p)$ into the master equation, the passive HML pulsewidth can be derived from the following equation obtained under steady-state condition,

$$\frac{D_g}{\tau_p^2} = l_0 - \frac{g_0}{1 + \frac{W}{P_{SAT}(T_R/M)}}, \quad (3)$$

where $l_0 = l + q_0$ denotes the total cavity loss that includes the linear absorption of the saturable absorber, W is the pulse energy, and P_{SAT} is the saturated power of the saturable absorber. In particular, T_R/M is the round-trip time of the cavity as well as the reciprocal repetition rate of the passive HML-EDFL pulse train. This equation clearly indicates the relationship between the pulsewidth and the HML order M. After the derivation under an approximation of the passive HML at near threshold (with $g_0 \approx l_0$), the passive HML pulsewidth can be simplified as,

$$\begin{aligned}\tau_p &= \sqrt{D_g\left[l_0 - \frac{g_0}{1 + \frac{W}{P_{SAT}(T_R/M)}}\right]^{-1}}\\ &= \sqrt{\frac{D_g[P_{SAT}(T_R/M) + W]}{l_0[P_{SAT}(T_R/M) + W] - g_0 P_{SAT}(T_R/M)}}\\ &= \sqrt{\frac{\frac{D_g}{l_0}\left[1 + \frac{P_{SAT}(T_R/M)}{W}\right]}{1 - \frac{(g_0 - l_0)}{l_0}\frac{P_{SAT}(T_R/M)}{W}}} \cong \sqrt{\frac{D_g}{l_0}\left[1 + \frac{P_{SAT}T_R}{W}\frac{1}{M}\right]}.\end{aligned} \quad (4)$$

In (4), note that the passive HML pulsewidth reveals an inverse proportionality with the HML order M. The passively mode-locked EDFL exhibits a maximum pulsewidth of $\tau_p = [D_g(1 + P_{SAT}T_R/WM)/l_0]^{0.5}$, which can be significantly shortened to $\tau_p = [D_g/l_0]^{0.5}$ at an extremely high HML order. Due to the inverse square-root function and the larger gain needed to obtain a higher HML output, the pulse-shortening force [defined as the ratio of second-harmonic generation (SHG) peak intensity to the square of fundamental average power] [22] becomes smaller at higher HML orders, and the higher order operation becomes more unstable. Therefore, the optimal condition that can be obtained in this work is limited at the HML order $M = 6$ with a pulsewidth of 1.9 ps. The experimental results almost confirm such an inverse square-root dependence except for a small deviation at lower HML orders. As the intracavity pumping power and the pulse intensity increase, the carrier recombination time reduces, and the frequency of absorption bleaching concurrently increases. When the pumping power is sufficiently large enough to provide high gain in the EDFL cavity, the saturated absorption frequency of CNT also increases to facilitate HML within one round-trip of the laser pulse. Both the experimental and simulated results indicate that the intracavity circulating intensity determines the highest HML order of the EDFL output. On the other hand, the HML order at a sufficiently high pumping level can be controlled by adjusting the PC prior to the SWCNT saturable absorber, which effectively adjusts the circulating intensity passing through the SWCNT saturable absorber to control the absorption bleaching frequency of the saturable absorption.

4. Conclusion

An SWCNT-doped PVA film is employed as a fast saturable absorber to induce up to sixth-order passive HML-EDFL with either all-PC or all-APC connector-based EDFL cavity configurations. Both the all-PC and the all-APC connector-based passive HML-EDFL systems can deliver stable pulse trains with the robust setup of EDFL fiber-ring; however, the all-PC connector-based system requires a larger pumping power to initiate mode-locking at the same HML order. In particular, the all-APC connector-based HML-EDFL scheme can provide a shorter pulsewidth associated with a broader spectral linewidth than the all-PC connector-based system. In comparison to the pulsewidth of 2.9–5.2 ps delivered by the all-PC connector system, the all-APC connector system further shortens the pulsewidth from 3.8 to 1.9 ps as the HML order increases from first to sixth. Concurrently, the spectral linewidth is broadened from 0.7 to 1.36 nm. At the sixth-order HML condition, either the all-PC or the all-APC connector-based EDFL can deliver a nearly transform-limited pulse with time–bandwidth product of 0.32. The SNRs obtained at different HML orders remain nearly constant at $\sim$40 dB; however, the RF spectral analysis reveals a relatively strong competition between the fundamental and the harmonic frequency components especially at higher order HML conditions. This phenomenon inevitably introduces the unequalized peak amplitudes among adjacent pulses, thus leading to an SMSR saturating at 32 dB under higher HML operation. The correlation between the HML-EDFL pulsewidth and the HML order is derived from the modified Haus' master equation. By solving the equation with a solution of hyperbolic secant function, the HML-EDFL pulsewidth shows an inverse proportionality with the square root of the HML order. In experiment, the change of HML order is preliminarily demonstrated by adjusting the pumping power of the passive HML-EDFL. The frequency of the saturated absorption in SWCNT can be increased by enhancing the pumping power in the EDFL cavity, which also facilitates HML within one round-trip time. The experiment indicates that the intracavity circulating intensity determines the highest HML order of the passively mode-locked EDFL output.

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