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(54) SYSTEM AND METHOD FOR AMPLIFYING AN OPTICAL SEED BEAM

SYSTEM UND VERFAHREN ZUR VERSTÄRKUNG EINES OPTISCHEN SEED-STRAHLS

SYSTÈME ET PROCÉDÉ D’AMPLIFICATION D’UN FAISCEAU OPTIQUE D’ENSEMENCEMENT

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- **GREGORY D. GOODNO ET AL: "Suppression of Stimulated Brillouin Scattering in Kilowatt Fiber Amplifiers using Nonlinear Spectral Compression", LASER CONGRESS 2018 (ASSL), 4 November 2018 (2018-11-04), page ATu6A.2, XP055621862, Washington, D.C. DOI: 10.1364/ASSL.2018.ATu6A.2 ISBN: 978-1-943580-48-4**
- **GREGORY D. GOODNO ET AL: "Suppression of stimulated Brillouin scattering in high power fibers using nonlinear phase demodulation", OPTICS EXPRESS, vol. 27, no. 9, 24 April 2019 (2019-04-24) , page 13129, XP055621849, DOI: 10.1364/OE.27.013129**

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Description

GOVERNMENT CLAUSE

[0001] This invention was made with Government support under Contract No. FA9451-18-C-0101 awarded by the Air Force Research Laboratory. The Government has certain rights in this invention.

BACKGROUND

Field

[0002] This disclosure relates generally to a fiber laser amplifier having high power and narrow linewidth and, more particularly, to a fiber laser amplifier system including an electro-optical modulator (EOM) that applies a frequency modulation (FM) signal to a seed beam to broaden its linewidth and applies an amplitude modulation (AM) signal to the seed beam that is synchronized with the FM signal, where the modulated seed beam is amplified by a non-linear fiber amplifier so that self-phase modulation that phase modulates the seed beam as it propagates through the amplifier cancels the frequency modulation of the beam to recover the spectrum of the original seed beam.

Discussion

[0003] High power laser amplifiers have many applications, including industrial, commercial, military, etc. Designers of laser amplifiers are continuously investigating ways to increase the power of the laser amplifier for these and other applications. One known type of laser amplifier is a fiber laser amplifier that employs a doped fiber that receives a seed beam and a pump beam that amplifies the seed beam and generates the high power laser beam, where the fiber has an active core diameter of about 10-20 μm or larger.

[0004] Improvements in fiber laser amplifier designs have increased the output power of the fiber to approach its practical power and beam quality limit. To further increase the output power of a fiber amplifier some fiber laser systems employ multiple fiber laser amplifiers that combine the amplified beams in some fashion to generate higher powers. A design challenge for fiber laser amplifier systems of this type is to combine the beams from a plurality of fiber amplifiers in a manner so that the beams provide a single beam output such that the beam can be focused to a small focal spot. Focusing the combined beam to a small spot at a long distance (far-field) defines the quality of the beam.

[0005] In one known multiple fiber amplifier design, a master oscillator (MO) generates a seed beam that is split into a plurality of fiber seed beams each having a common wavelength, where each fiber beam is amplified. The amplified fiber seed beams are then collimated and directed to a diffractive optical element (DOE) that combines the coherent fiber beams into a single output beam. The DOE has a periodic structure formed into the element so that when the individual fiber beams each having a slightly different angular direction are redirected by the periodic structure all of the beams diffract from the DOE in the same direction. Each fiber beam is provided to a phase modulator that controls the phase of the beam so that the phase of all the fiber beams is maintained coherent. However, limitations on bandwidth and phasing errors limits the number of fiber beams that can be coherently combined, thus limiting the output power of the laser.

[0006] In another known multiple fiber amplifier design, a plurality of master oscillators (MOs) generate a plurality of fiber seed beams at a plurality of wavelengths, where each fiber seed beam is amplified. The amplified fiber seed beams are then collimated and directed to a diffraction grating, or other wavelength-selective element, that combines the different wavelength fiber beams into a single output beam. The diffraction grating has a periodic structure formed into the element so that when the individual fiber beams each having a slightly different wavelength and angular direction are redirected by the periodic structure all of the beams diffract from the diffraction grating in the same direction. However, limitations on bandwidth limit the number of fiber beams that can be wavelength-combined, thus limiting the output power of the laser.

[0007] To overcome these limitations and further increase the laser beam power, multiple master oscillators can be provided to generate seed beams at different wavelengths, where each of the individual wavelength seed beams is split into a number of fiber seed beams and where each group of fiber seed beams has the same wavelength and are mutually coherent. Each group of the coherent fiber seed beams at a respective wavelength are first coherently combined by a DOE, and then each group of coherently combined beams are directed to a spectral beam combination (SBC) grating at slightly different angles that diffracts the beams in the same direction as a single combined beam of multiple wavelengths. The SBC grating also includes a periodic structure for combining the beams at the different wavelengths.

[0008] It is often desirable that the output beam from a fiber amplifier be narrow linewidth, i.e., have a narrow frequency range, to improve beam quality. However, providing both high power and narrow linewidth has heretofore been challenging in the art because they are typically incompatible with each other because higher power typically requires a broader beam linewidth. More particularly, the phenomenon of stimulated Brillouin scattering (SBS), i.e., non-linear back-scattering of the beam as it propagates along the fiber amplifier, increases at narrower linewidths with small frequency ranges, which acts to reduce beam power. However, the wider the beam linewidth, the more difficult it is to coherently combine or spectrally combine beams from multiple fibers into a single beam through known beam combining techniques. Particularly, dispersion effects from an SBC grating require that the linewidth of the beams being amplified is narrow, where spectral dispersion causes the spectral components of the beam to be diffracted at different angles. In other words, for SBC, the spectral brightness of the seed beam directly limits the theoretical brightness of the combined beam output.

[0009] For coherent beam combining (CBC), the spectral brightness of the seed beam limits the combining efficiency because of imperfect matching of group delay and dispersion between amplifiers. Typically, the source spectral brightness is limited by SBS, and the seed beam source to the fiber amplifier must be frequency modulated to reduce the peak SBS gain and achieve the desired output power. The frequency modulation spectral broadening limits the attainable spectral brightness from a single fiber amplifier, thus limiting the system output.

[0010] In order to overcome these limitations, designers of fiber amplifiers typically employ one or more phase modulators before the amplification stage in the fiber amplifier to reduce the linewidth through frequency modulation. However, once the frequency modulation is applied to the beam before it is amplified by the fiber amplifier, that widening of the spectral content of the beam is carried through the amplifier resulting in a low spectral brightness amplified beam.

[0011] U.S. Patent No. 9,036,252 titled, Nonlinear Spectrally Narrowed Fiber Amplifier, issued May 19, 2015 to Goodno et al., assigned to the assignee of this application, discloses a fiber laser amplifier system that has high power and narrow linewidth for improved spectral brightness. The fiber amplifier system disclosed in the ‘252 patent includes a seed source providing an optical seed beam and a harmonic phase modulator that receives the seed beam and an RF drive signal so as to frequency modulate the seed beam using the drive signal to remove optical power from a main band or zeroth-order frequency of the seed beam and put the power into sideband frequencies separated by the frequency of the drive signal. A dispersion element receives the frequency modulated seed beam and provides temporal amplitude modulation of the seed beam. A non-linear fiber amplifier receives the frequency and amplitude modulated seed beam from the dispersion element and amplifies the seed beam, where the frequency modulation and self-phase modulation (SPM) caused by the non-linearity of the fiber amplifier combine to remove the optical power from the sideband frequencies and put it back into the zeroth-order frequency.

[0012] As generally discussed above, the ‘252 fiber amplifier system frequency modulates the seed beam and then uses dispersion to amplitude modulate the frequency modulated seed beam, where the amplitude modulation drives self-phase modulation caused by the non-linearity of the fiber amplifier to cause the spectrum of the beam as it is being amplified to be reduced to create the high power output beam having a narrow linewidth. Although this technique can effectively provide a high power and narrow linewidth beam as described, relying on dispersion to provide amplitude modulation of the seed beam is limited because the amplitude modulation is not precisely matched to the frequency modulation, which limits the efficiency of non-linear spectral compression in the fiber amplifier at higher modulation depths. More particularly, for low modulation depths and high non-linear fiber amplifiers the spectral compression in the fiber amplifier is effective. However, for lower amounts of non-linearity in the fiber amplifier, more dispersion is required to obtain deeper amplitude modulation of the beam. But, for larger amounts of dispersion the shape in time of the amplitude modulation does not precisely match the shape in time of the frequency modulation linewidth broadening, i.e., the amplitude modulation waveform is not perfectly sinusoidal, and thus the non-linear spectral compression will be inefficient and significant power will remain in the sidebands, which limits the amount the linewidth can be reduced. Therefore, there is a tradeoff between the spectral compression efficiency and higher SBS suppression.

[0013] Prior art can also be found in WO 2011/053816 A1 which generally relates to a method and system using phase modulation to reduce spectral broadening and in JP 2016 102811 A which generally relates to a pulse laser device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014]

Figure 1 is a schematic block diagram of an input portion of a fiber laser amplifier system not in accordance with the claimed invention, but useful for understanding the claimed invention, including separate EOMs for providing frequency modulation and amplitude modulation of a seed beam;

Figure 2 is a schematic block diagram of an input portion of a fiber laser amplifier system in accordance with the claimed invention including a single EOM for providing both frequency modulation and amplitude modulation of a seed beam;

Figure 3 is a schematic block diagram of a fiber laser amplifier system including a single EOM for providing both frequency modulation and amplitude modulation of a seed beam and employing CBC having matched B integrals between the fiber amplifiers;

Figure 4 is a schematic block diagram of a fiber laser amplifier system including a single EOM for providing both frequency modulation and amplitude modulation of a seed beam and employing CBC having unmatched B integrals between the fiber amplifiers; and

Figure 5 is a schematic block diagram of a fiber laser amplifier system including multiple channels each having a single EOM for providing both frequency modulation and amplitude modulation of a seed beam and employing SBC.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0015] The following discussion of the embodiments of the disclosure directed to a fiber laser amplifier that provides frequency modulation and amplitude modulation of a seed beam to increase beam power and reduce beam linewidth is merely exemplary in nature, and is in no way intended to limit the scope of the invention or its applications or uses, the scope of the invention being defined by the claims.

[0016] As discussed above, fiber laser amplifiers are limited in spectral brightness because of the incompatibility between high power and narrow linewidth. In order to overcome this incompatibility, the present disclosure proposes employing both frequency modulation and amplitude modulation to broaden the linewidth of a seed beam and then using self-phase modulation created by the non-linearity in the high power fiber amplifier to spectrally compress the linewidth of the amplified beam to near that of the original un-broadened seed spectrum.

[0017] Figure 1 is a schematic block diagram of a portion of a fiber laser amplifier system 10 that includes a master oscillator 12 that generates a seed beam on line 14 having a particular wavelength. The seed beam is provided to an auxiliary RF electro-optical modulator (EOM) 16 that is controlled by an auxiliary RF driver 18 to provide frequency modulation. The frequency modulation provided by the EOM 16 presents a conventional technique for providing frequency modulation broadening, such as white noise or pseudo-random bit sequence (PRBS), and may not be required or desired in some amplifier systems. It is noted that the EOM 16 can be at any suitable location in the system 10 before the seed beam is amplified. The laser field $E_1(t)$ following the auxiliary EOM 16 will be of the form:

$$E_1(t) = exp[i\phi(t)]. \qquad (1)$$

[0018] As can be seen from equation (1), the laser field amplitude is constant in time and its phase is time-varying with the function $\phi(t)$ imposed by the EOM 16.

[0019] The modulated seed beam from the EOM 16 is then sent to an FM EOM 20 that also receives a RF drive signal $f(t)$ from an RF driver 22. The EOM 20 imposes the RF drive signal onto the phase of the optical seed beam to vary the frequency of the seed beam in time and provide the frequency modulation. The frequency modulated field output from the EOM 20 is of the form:

$$E_2(t) = E_1(t)e^{i\beta f(t)}, \qquad (2)$$

where the drive signal $f(t)$ is assumed to be zero-mean (time-averaged), and normalized to unity, and β is a frequency modulation depth in radians.

[0020] The frequency modulation provides a time dependent change in the phase of the seed beam that broadens the beam's linewidth, where the broad linewidth provides SBS suppression. In one non-limiting example for discussion purposes herein, the RF drive signal provided by the driver 22 is a single-tone sinusoidal signal $f(t) = \sin(\omega_m t)$, where $\omega_m/2\pi$ is a modulation frequency that could 32 GHz, which is twice the Stokes frequency shift caused by SBS in a fused silica fiber. However, it is noted that other high frequency sinusoidal drive signals can also be employed in various applications. More generally, the drive signal $f(t)$ need not be sinusoidal and can in fact be of any functional form, including for example, a PRBS format, or a shaped noise spectrum.

[0021] The frequency modulation provided by the EOM 20 generates an optical seed beam that includes broadened spectral linewidth that is defined by the functional form $f(t)$ and modulation depth β of the drive signal. In the non-limiting example described herein, the spectral content of the seed beam will include frequency sidebands separated by 32 GHz. The modulation depth β of the RF drive signal from the driver 22 is selected depending on the desired spectral linewidth, where a higher modulation depth signal would generate a broader linewidth. For example, in the non-limiting described example herein, the modulation depth β of the drive signal may be selected to remove all of the power from the zeroth-order frequency of the seed beam in the EOM 20. Alternately, the modulation depth β of the drive signal may be selected to create equal amplitude powers in the zeroth and +/- first order sideband frequencies of the seed beam in the EOM 20. Alternately, the modulation depth β of the drive signal may be selected to create a large number of sidebands of the seed beam in the EOM 20.

[0022] The frequency modulated seed beam is then sent to an AM EOM 24 that receives an RF drive signal from an RF driver 26 that provides amplitude modulation of the seed beam, i.e., varies the power of the seed beam in time, where the EOM 24 imposes the drive signal onto the amplitude of the optical seed beam to provide the amplitude modulation. The RF driver 26 is synchronized with the RF driver 22 via the common underlying drive signal *f(t)* so as to produce an AM/FM field output from the EOM 24 of the form:

$$E_3(t) = \sqrt{1 - \tfrac{\beta}{B} f(t)}\ E_2(t) = \sqrt{1 - \tfrac{\beta}{B} f(t)} e^{i\beta f(t)} E_1(t), \tag{3}$$

where the parameter *B* is a non-linear phase shift (in radians) due to self-phase modulation that is associated with the fiber amplifier 28 that will be seeded by the AM/FM source, i.e., the amplified high power beam emitted from the fiber amplifier 28 will experience a nonlinear phase shift of parameter *B*.

[0023] Without the frequency modulation, the amplitude modulation $\sqrt{1 - \tfrac{\beta}{B} f(t)}$ of the seed beam would provide very little broadening of the seed beam linewidth. As is apparent from inspection of equation (3), the amplitude modulation is synchronized with the frequency modulation so that peaks of the amplitude align with valleys of the phase. Because the EOM 24 directly provides amplitude modulation of the beam and does not rely on dispersion to provide amplitude modulation as in the '252 patent, the amplitude modulation term $\sqrt{1 - \tfrac{\beta}{B} f(t)}$ and the frequency modulation term $e^{i\beta f(t)}$ can be precisely matched even at high modulation depths β and/or low amplifier non-linearity *B*.

[0024] It is also apparent from equation (3) that it is not necessary that the frequency modulation of the seed beam occur before the amplitude modulation of the seed beam, where the order of the EOMs 20 and 24 can be switched. In accordance with the claimed invention, the FM and AM EOMs 20 and 24 are combined as a single device. This embodiment is illustrated by fiber amplifier system 40 in figure 2, where like elements to the system 10 are identified by the same reference number. In the system 40 the EOMs 20 and 24 are combined as a single AM/FM EOM 42 that receives synchronized drive signals from an RF driver 44 and imposes amplitude modulation and frequency modulation on the seed beam at the same time. A second drive signal from the RF driver 44 may be a variation of the first drive signal from the RF driver 44 that has been phase shifted and amplified for the amplitude modulation. The EOM 42 can be any device suitable for the purposes described herein, such as the commercially available broadband, low-loss, $LiNbO_3$ electro-optic dual-drive Mach-Zehnder interferometric intensity modulator available from EOspace™.

[0025] The amplitude and frequency modulated seed beam is then sent to a non-linear fiber amplifier 28, which may be a plurality of fiber amplification stages each including a pump beam and a length of doped fiber, such as a ytterbium (Yb) doped length of fiber having a 10 - 20 μm core, and the amplified output beam is provided on fiber 30. The amplitude modulation and the frequency modulation are synchronized per equation (3) so that for a given non-linearity parameter *B* of the fiber amplifier 28 an optimal spectral compression of the amplified beam can be provided for high power and narrow linewidth. The combined amplitude modulated and frequency modulated seed beam is tailored to the non-linearity of the fiber amplifier 28 so that the spectral linewidth is broad when the seed beam is sent to the amplifier 28. Because of the non-linear Kerr effect in the fiber amplifier 28, where the power-dependent refractive index of the fiber causes greater phase shifts in the optical beam at higher power, the interaction of the amplitude modulated power variations in the seed beam creates synchronous phase shifts of the beam in the fiber amplifier 28. The time-dependent non-linear phase that arises due to this self phase modulation is:

$$SPM(t) = B|E_3(t)|^2 = B\left[1 - \tfrac{\beta}{B} f(t)\right] = B - \beta f(t). \tag{4}$$

[0026] Consequently, the amplified field emitted from the fiber amplifier 28 is:

$$E_4(t) = E_3(t)e^{iSPM(t)} = \sqrt{1 - \frac{\beta}{B} f(t)} e^{i\beta f(t)} e^{i[B - \beta f(t)]} E_1(t)$$

$$= \sqrt{1 - \tfrac{\beta}{B} f(t)} e^{iB} E_1(t). \tag{5}$$

[0027] Equation (5) shows that the phase shift *SPM*(*t*) that occurs due to the non-linear self-phase modulation cancels the frequency modulation $\beta f(t)$ that was previously provided from the EOM 20. The only remaining phase term is a constant global phase shift *B* that does not affect the optical spectrum. As the seed beam propagates through the fiber amplifier 28 and is amplified, the non-linear Kerr effect causes self-phase modulation in the amplifier 28 that causes power of the beam to shift back to the original linewidth associated with the field $E_1(t)$ so as to provide a high power beam with a narrow linewidth at the fiber amplifier output.

[0028] By cancelling the frequency modulation in the optical signal through this effect, the spectrum of the original beam $E_1(t)$ can be nearly perfectly recovered at the output of the amplifier 28, with only a small amount of linewidth broadening arising from the residual amplitude modulation term $\sqrt{1-\frac{\beta}{B}f(t)}$. The change in the spectrum between the input and output of the amplifier 28 (fields $E_3(t)$ and $E_4(t)$, respectively) reduces the spectral overlap of backscattered SBS from different locations in the length of the fiber amplifier 28. This increases the SBS threshold in comparison to a seed spectrum without modulation. In other words, as a result of there being broader spectral linewidth of the seed beam represented by field $E_3(t)$ when the seed beam is frequency modulated there is reduced back-scattering of light that is spectrally overlapped with the linewidth of the amplified beam represented by field $E_4(t)$. As the optical power is spectrally compressed by accumulated self-phase modulation as the beam propagates through the fiber amplifier 28, the SBS increases, but it is limited by the reduction of the spectral brightness earlier in the beam propagation.

[0029] As discussed, the seed beam is initially modulated to broaden its spectral linewidth and the power is spectrally compressed into the original linewidth associated with the field $E_1(t)$ as the seed beam is amplified and the non-linear phase accumulates. The back-scattered SBS Stokes light from any point in the fiber amplifier 28 will be representative of the local spectrum at that point. Since the forward propagating beam through much of the fiber amplifier 28 has very low spectral overlap with the return wave back-scattered near the output end of the fiber amplifier 28, the SBS gain will be much lower than without the AM/FM modulation. This increases the threshold for SBS and enables a higher spectral brightness output than conventional techniques for frequency modulation without self-phase modulation compression. Moreover, for the non-limiting case of sinusoidal modulation, a judicious choice of the modulation frequency to be twice the SBS Stokes shift, i.e., 32 GHz, largely can eliminate self-seeding effects from reducing the SBS threshold.

[0030] To ensure maximum compression efficiency into the original spectral linewidth associated with the input field $E_1(t)$, the magnitude of the amplitude modulation can be adjusted to be in accordance with the optimized value $\sqrt{1-\frac{\beta}{B}f(t)}$ described by equation (3). This adjustment can be performed by either changing the modulation depth of the amplitude modulation drive voltage, or adding a passive delivery fiber after the amplifier 28, which increases the B-integral, or by changing the power of the amplifier 28, which proportionately changes the B-integral.

[0031] An example set of modulation parameters that are useful for illustrating SBS suppression are described below. The fiber amplifier 28 can be a 2 kW fiber amplifier with a typical B-integral of B = 10 radians. The modulation RF drive signal is chosen to be $f(t) = \sin(\omega_m t)$, where $\omega_m/2\pi = 32$ GHz. By selecting a frequency modulation depth $\beta = 2.4$ radians, the spectral linewidth of the FM field $E_2(t)$ is broadened to ~2 $\beta\omega_m/2\pi$ = 150 GHz. The EOM 24 imposes synchronous amplitude modulation as described by equation (3), so that the AM/FM field is:

$$E_3(t) = \sqrt{1 - 0.24 * \sin(\omega_m t)}\, e^{2.4i*sin(\omega_m t)} E_1(t). \qquad (6)$$

[0032] The resulting power fluctuations are sinusoidal with ~48% peak-to-peak modulation depth relative to the unmodulated continuous wave power level. Upon amplification in the non-linear fiber amplifier 28, the accumulated SPM cancels the imposed frequency modulation so that the output field is simply:

$$E_4(t) = \sqrt{1 - 0.24 * \sin(\omega_m t)}\, e^{10i} E_1(t). \qquad (7)$$

[0033] The spectral linewidth of the amplified output field is very similar to that of the original input field $E_1(t)$. Calculations show that due to the reduced spectral brightness of the seed beam over much of the length of the fiber amplifier 28, the expected SBS threshold for this AM/FM configuration should be increased by a factor of ~2x compared to the unmodulated case. This enables ~2x higher spectral brightness output power than can be otherwise attained.

[0034] The fiber laser amplifier systems 10 and 40 discussed above can be part of any suitable fiber amplifier system, where those skilled in the art would understand how the various components would be arranged consistent with the discussion herein. For example, if the fiber amplifier system 10 or 40 is part of a coherent beam combining (CBC) fiber amplifier system comprising multiple parallel fiber amplifiers 28 with identical (matched) B-integrals, the frequency modulated seed beam would be split after the EOM 24 or 42 into multiple channels. Each channel would also include a phase actuator. If the fiber amplifiers 28 in each channel were not identically matched in B-integral, then the seed beam would be split between the EOM 16 and the EOM 20 or 42 and components downstream of the EOM 16 would be duplicated for each channel. If the fiber amplifier system 10 or 40 is part of a spectral beam combining (SBC) fiber amplifier system, then there would be several of the fiber amplifier systems 10 or 40, each operating at different wavelengths and having no common components. These fiber amplifier systems are further discussed below.

[0035] Figure 3 is a schematic block diagram of a fiber laser amplifier system 50 that includes a single EOM for providing both frequency modulation and amplitude modulation of a seed beam similar to the system 40, where like elements are identified by the same reference number, and employs CBC having matched B integrals between the fiber amplifiers 28. The system 50 includes a beam splitter 52 after the EOM 42 that splits the modulated seed beam into a plurality of channels 54. The modulated seed beam in each of the channels 54 is sent to a phase actuator 56 that controls the phase of the modulated seed beams in each of the channels 54 so that they are in phase with each other. The phase controlled and modulated seed beams are then amplified by the amplifier 28 in each channel 54 and the amplified beams are combined by beam combining optics 58 that includes the proper optics and gratings for CBC of beams having a common wavelength, and a combined beam is output therefrom.

[0036] Figure 4 is a schematic block diagram of a fiber laser amplifier system 60 that includes a single EOM for providing both frequency modulation and amplitude modulation of a seed beam similar to the systems 40 and 50, where like elements are identified by the same reference number, and employs CBC having unmatched B integrals between the fiber amplifiers 28. The system 60 includes a beam splitter 52 that splits the seed beam prior to being modulated by the EOM 42, where the split seed beams are sent to a plurality of channels 62. The split beam in each of the channels 62 is sent to the EOM 42 for that channel 62 and the modulated seed beam is sent to the phase actuator 56 that controls the phase of the modulated seed beams in each of the channels 54 so that they are in phase with each other. The phase controlled and modulated seed beams are then amplified by the amplifier 28 in each channel 54 and then the amplified beams are combined by the beam combining optics 58 to be output therefrom as a combined beam.

[0037] Figure 5 is a schematic block diagram of a fiber laser amplifier system 70 including multiple channels 72 each having one of the laser amplifier systems 40 and 50, where like elements are identified by the same reference number, and where each MO 12 in each channel 72 operates at a separate wavelength suitable for SBC. The amplified beams from the amplifiers 28 in each channel 72 are combined by beam combining optics 74 that employs the proper gratings and optics for SBC of beams having different wavelengths to generate a combined beam.

[0038] The foregoing discussion discloses and describes merely exemplary embodiments of the present disclosure. One skilled in the art will readily recognize from such discussion and from the accompanying drawings and claims that various changes, modifications and variations can be made therein without departing from the scope of the invention as defined in the following claims.

Claims

1. A fiber amplifier system (40) comprising:

an optical source (12) providing an optical seed beam;
an auxiliary electro-optical modulator, EOM, (16) configured to frequency modulate the seed beam to provide frequency modulation broadening;
a single combined frequency modulation, FM, and amplitude modulation, AM, EOM (42) configured to be responsive to the seed beam, a first RF drive signal (44) and a second RF drive signal (44), said FM and AM EOM (42) configured to frequency modulate the seed beam by providing a time dependent change in the phase of the seed beam using the first drive signal (44) so as to broaden its spectral linewidth and amplitude modulate the seed beam using the second drive signal (44) so as to vary the power of the seed beam in time and provide an amplitude modulated seed beam that is synchronized with the frequency modulated seed beam; and
a non-linear fiber amplifier (26) configured to receive the AM and FM modulated seed beam and configured to amplify the seed beam, wherein the amplitude modulated seed beam is configured to cause self-phase modulation in the fiber amplifier (26) that phase modulates the seed beam as it is being amplified by the fiber amplifier (26) that acts to cancel the spectral linewidth broadening caused by the frequency modulation of the combined FM and AM EOM (42), wherein peaks of the amplitude modulation of the seed beam caused by the second drive signal align with valleys of the phase modulation of the seed beam caused by the first drive signal.

2. The system (40) according to claim 1 where the second drive signal (44) is a variation of the first drive signal (44) that has been phase shifted and amplified for the amplitude modulation.

3. The system (40) according to claim 1 wherein the first drive signal (44) and the second drive signal (44) are single-tone sinusoid signals.

4. The system (40) according to claim 3 wherein the amplitude of the first drive signal (44) is selected to remove most of the power from the zeroth-order frequency of the seed beam by the FM and AM EOM (42).

5. The system (40) according to claim 3 wherein the amplitude of the first drive signal (44) is selected to create equal amplitude powers in the zeroth and +/first order frequencies of the seed beam in the FM and AM EOM (42).

6. The system (40) according to claim 5 wherein the first drive signal (44) has a frequency of 32 GHz.

7. The system (40) according to claim 1 wherein the optical source (12) is a master oscillator (12).

8. The system (40) according to claim 1 wherein the fiber amplifier system (40) is part of a coherent beam combining, CBC, fiber amplifier system (50) or a spectral beam combining, SBC, fiber amplifier system (70).

9. The system (40) of claim 1, wherein the frequency modulation is provided by the equation:

$$E_2(t) = E_1(t)e^{i\beta f(t)}$$

wherein $E_2(t)$ is the frequency modulated seed beam generated by the combined AM and FM EOM (42), wherein the seed beam is defined by $E_1(t) = exp[i\phi(t)]$, with the function $\phi(t)$ being imposed by the auxiliary EOM (16), f(t) is a frequency of the first RF drive signal (44), and β is a frequency modulation depth of the first RF drive signal (44) in radians.

10. The system (40) according to claim 1, wherein the amplitude modulation is provided by the equation:

$$E_3(t) = \sqrt{1-\frac{\beta}{B}f(t)}\;E_2(t) = \sqrt{1-\frac{\beta}{B}f(t)}e^{i\beta f(t)}E_1(t)$$

wherein the seed beam is defined by $E_1(t) = exp[i\phi(t)]$, with the function $\phi(t)$ being imposed by the auxiliary EOM (16), wherein $E_2(t)$ is the frequency modulated seed beam generated by the combined AM and FM EOM (42), wherein the seed beam is defined by $E_1(t) = exp[i\phi(t)]$, with the function $\phi(t)$ being imposed by the auxiliary EOM (16), f(t) is a frequency of the first RF drive signal (44), β is a frequency modulation depth of the first RF drive signal (44) in radians, B is a non-linear phase shift in radians and $E_3(t)$ is the amplified modulated seed beam.

11. A method for amplifying an optical seed beam, said method comprising:

frequency modulating the seed beam, in an auxiliary electro-optical modulator, EOM, (16), to provide frequency modulation broadening;
frequency modulating the seed beam by providing a time dependent change in the phase of the seed beam using a first RF drive signal (44) so as to broaden its spectral linewidth;
amplitude modulating the seed beam using a second RF drive signal (44) so as to vary the power of the seed beam in time and provide an amplitude modulated seed beam that is synchronized with the frequency modulated seed beam, wherein frequency modulating the seed beam using the first drive signal and amplitude modulating the seed beam using the second drive signal occurs in a single combined frequency modulation, FM, and amplitude modulation, AM, EOM (42); and
amplifying the frequency and amplitude modulated seed beam in a non-linear fiber amplifier (28) so that the amplitude modulated seed beam causes self-phase modulation caused in the fiber amplifier (28) that phase modulates the seed beam as it is being amplified by the fiber amplifier (28) that acts to cancel the spectral linewidth broadening caused by the frequency modulation of the combined frequency modulation, FM, and amplitude modulation, AM, EOM (42), wherein peaks of the amplitude modulation of the seed beam caused by

the second drive signal align with valleys of the phase modulation of the seed beam caused by the first drive signal.

12. The method according to claim 11 wherein the first drive signal (44) and the second drive signal (44) are single-tone sinusoid signals.

13. The method according to claim 12 wherein the amplitude of the first drive signal (44) is selected to remove most of the power from the zeroth-order frequency of the seed beam during the frequency modulation.

14. The method according to claim 12 wherein the amplitude of the first drive signal (44) is selected to create equal amplitude powers in the zeroth and +/- first order frequencies of the seed beam during the frequency modulation.

15. The method according to claim 12 wherein the first drive signal (44) has a frequency of 32 GHz.

Patentansprüche

1. Ein Faserverstärkersystem (40), das Folgendes umfasst:

   eine optische Quelle (12), die einen optischen Keimstrahl erzeugt;
   einen elektro-optischen Hilfsmodulator (16), der so konfiguriert ist, dass er den Keimstrahl frequenzmoduliert, um eine Frequenzmodulationsverbreiterung zu erzielen;
   einen einzelnen kombinierten Frequenzmodulations- (FM) und Amplitudenmodulations- (AM) EOM (42), der so konfiguriert ist, dass er auf den Keimstrahl, ein erstes HF-Ansteuersignal (44) und ein zweites HF-Ansteuersignal (44) anspricht, wobei der FM- und AM-EOM (42) so konfiguriert ist, dass er den Keimstrahl durch Bereitstellen einer zeitabhängigen Änderung in der Phase des Keimstrahls unter Verwendung des ersten Ansteuersignals (44) frequenzmoduliert, um seine spektrale Linienbreite zu verbreitern, und den Keimstrahl unter Verwendung des zweiten Ansteuersignals (44) amplitudenmoduliert, um die Leistung des Keimstrahls in der Zeit zu variieren und einen amplitudenmodulierten Keimstrahl bereitzustellen, der mit dem frequenzmodulierten Keimstrahl synchronisiert ist; und
   einen nichtlinearen Faserverstärker (26), der so konfiguriert ist, dass er den AM- und FM-modulierten Keimstrahl empfängt, und der so konfiguriert ist, dass er den Keimstrahl verstärkt, wobei der amplitudenmodulierte Keimstrahl so konfiguriert ist, dass er eine Selbstphasenmodulation in dem Faserverstärker (26) verursacht, die den Keimstrahl phasenmoduliert, während er durch den Faserverstärker (26) verstärkt wird, was bewirkt, dass die spektrale Linienbreitenverbreiterung, die durch die Frequenzmodulation des kombinierten FM- und AM-EOM (42) verursacht wird, aufgehoben wird, wobei die Spitzen der Amplitudenmodulation des Keimstrahls, die durch das zweite Ansteuersignal verursacht wird, mit den Tälern der Phasenmodulation des Keimstrahls, die durch das erste Ansteuersignal verursacht wird, übereinstimmen.

2. Das System (40) nach Anspruch 1, wobei das zweite Ansteuersignal (44) eine Variation des ersten Ansteuersignals (44) ist, das für die Amplitudenmodulation phasenverschoben und verstärkt wurde.

3. Das System (40) nach Anspruch 1, wobei das erste Ansteuersignal (44) und das zweite Ansteuersignal (44) Eintonsinussignale sind.

4. Das System (40) nach Anspruch 3, bei dem die Amplitude des ersten Ansteuersignals (44) so gewählt wird, dass der größte Teil der Leistung aus der Frequenz nullter Ordnung des Keimstrahls durch den FM- und AM-EOM (42) entfernt wird.

5. Das System (40) nach Anspruch 3, wobei die Amplitude des ersten Ansteuersignals (44) so gewählt wird, dass gleiche Amplitudenleistungen in den Frequenzen nullter und +/- erster Ordnung des Keimstrahls im FM- und AM-EOM (42) erzeugt werden.

6. Das System (40) nach Anspruch 5, wobei das erste Ansteuersignal (44) eine Frequenz von 32 GHz hat.

7. Das System (40) nach Anspruch 1, wobei die optische Quelle (12) ein Master-Oszillator (12) ist.

8. Das System (40) nach Anspruch 1, wobei das Faserverstärkersystem (40) Teil eines Faserverstärkersystems (50) zur kohärenten Strahlvereinigung (CBC) oder eines Faserverstärkersystems (70) zur spektralen Strahlvereinigung

(SBC) ist.

9. Das System (40) nach Anspruch 1, wobei die Frequenzmodulation durch die Gleichung bereitgestellt wird:

$$E_2(t) = E_1(t)e^{i\beta f(t)}$$

wobei E_2 (t) der frequenzmodulierte Keimstrahl ist, der von dem kombinierten AM- und FM-EOM (42) erzeugt wird, wobei der Keimstrahl definiert ist durch $E_1(t) = exp[i\phi(t)]$definiert ist, wobei die Funktion $\phi(t)$ von dem Hilfs-EOM (16) auferlegt wird, f(t) eine Frequenz des ersten HF-Treibersignals (44) ist und β eine Frequenzmodulationstiefe des ersten HF-Treibersignals (44) in Radiant ist.

10. Das System (40) nach Anspruch 1, wobei die Amplitudenmodulation durch die Gleichung bereitgestellt wird:

$$E_3(t) = \sqrt{1 - \frac{\beta}{B}f(t)}\ \ E_2(t) = \sqrt{1 - \frac{\beta}{B}f(t)}e^{i\beta f(t)}E_1(t)$$

wobei der Keimstrahl definiert ist durch $E_1(t) = exp[i\phi(t)]$definiert ist, wobei die Funktion $\phi(t)$ durch das Hilfs-EOM (16) auferlegt wird, wobei E_2 (t) der frequenzmodulierte Keimstrahl ist, der durch das kombinierte AM- und FM-EOM (42) erzeugt wird, wobei der Keimstrahl definiert ist durch $E_1(t) = exp[i\phi(t)]$wobei die Funktion $\phi(t)$ von dem Hilfs-EOM (16) vorgegeben wird, f(t) eine Frequenz des ersten HF-Treibersignals (44) ist, β eine Frequenzmodulationstiefe des ersten HF-Treibersignals (44) in Radiant ist, B eine nichtlineare Phasenverschiebung in Radiant ist und E_3 (t) der verstärkte modulierte Keimstrahl ist.

11. Ein Verfahren zur Verstärkung eines optischen Keimstrahls, wobei das Verfahren umfasst:

Frequenzmodulation des Keimstrahls in einem elektro-optischen Hilfsmodulator (16), um die Frequenzmodulation zu verbreitern;
Frequenzmodulation des Keimstrahls durch eine zeitabhängige Änderung der Phase des Keimstrahls unter Verwendung eines ersten HF-Treibersignals (44), um seine spektrale Linienbreite zu verbreitern;
Amplitudenmodulation des Keimstrahls unter Verwendung eines zweiten HF-Ansteuersignals (44), um die Leistung des Keimstrahls zeitlich zu variieren und einen amplitudenmodulierten Keimstrahl bereitzustellen, der mit dem frequenzmodulierten Keimstrahl synchronisiert ist, wobei die Frequenzmodulation des Keimstrahls unter Verwendung des ersten Ansteuersignals und die Amplitudenmodulation des Keimstrahls unter Verwendung des zweiten Ansteuersignals in einem einzigen kombinierten Frequenzmodulations-, FM, und Amplitudenmodulations-, AM, EOM (42) erfolgt; und
Verstärken des frequenz- und amplitudenmodulierten Keimstrahls in einem nichtlinearen Faserverstärker (28), so dass der amplitudenmodulierte Keimstrahl eine Selbstphasenmodulation verursacht, die in dem Faserverstärker (28) verursacht wird, der den Keimstrahl phasenmoduliert, während er durch den Faserverstärker (28) verstärkt wird, was bewirkt, dass die spektrale Linienbreitenverbreiterung, die durch die Frequenzmodulation der kombinierten Frequenzmodulation verursacht wird, aufgehoben wird, FM, und der Amplitudenmodulation, AM, EOM (42) verursacht wird, wobei die Spitzen der Amplitudenmodulation des Keimstrahls, die durch das zweite Ansteuersignal verursacht wird, mit den Tälern der Phasenmodulation des Keimstrahls, die durch das erste Ansteuersignal verursacht wird, fluchten.

12. Das Verfahren nach Anspruch 11, wobei das erste Ansteuersignal (44) und das zweite Ansteuersignal (44) Eintonsinussignale sind.

13. Das Verfahren nach Anspruch 12, bei dem die Amplitude des ersten Ansteuersignals (44) so gewählt wird, dass während der Frequenzmodulation der größte Teil der Leistung aus der Frequenz nullter Ordnung des Keimstrahls entfernt wird.

14. Das Verfahren nach Anspruch 12, wobei die Amplitude des ersten Ansteuersignals (44) so gewählt wird, dass während der Frequenzmodulation gleiche Amplitudenleistungen in den Frequenzen nullter und +/- erster Ordnung des Keimstrahls erzeugt werden.

15. Das Verfahren nach Anspruch 12, wobei das erste Ansteuersignal (44) eine Frequenz von 32 GHz hat.

Revendications

1. Un système d'amplificateur à fibre (40) comprenant:

une source optique (12) fournissant un faisceau de semences optiques;
un modulateur électro-optique auxiliaire (EOM) (16) configuré pour moduler la fréquence du faisceau de semences afin d'obtenir un élargissement de la modulation de fréquence;
une EOM (42) combinant modulation de fréquence (FM) et modulation d'amplitude (AM), configurée pour réagir au faisceau de semences, à un premier signal de commande RF (44) et à un second signal de commande RF (44), ladite modulation de fréquence et modulation d'amplitude EOM (42) configurée pour moduler en fréquence le faisceau de semences en apportant un changement dépendant du temps à la phase du faisceau de semences à l'aide du premier signal de commande (44) de manière à élargir sa largeur de ligne spectrale et à moduler en amplitude le faisceau de semences à l'aide du second signal de commande (44) de manière à faire varier la puissance du faisceau de semences dans le temps et à fournir un faisceau de semences modulé en amplitude qui est synchronisé avec le faisceau de semences modulé en fréquence; et
un amplificateur à fibre non linéaire (26) configuré pour recevoir le faisceau de semences modulé en AM et FM et configuré pour amplifier le faisceau de semences, dans lequel le faisceau de semences modulé en amplitude est configuré pour provoquer une modulation de phase automatique dans l'amplificateur à fibre (26) qui module la phase du faisceau de semences lorsqu'il est amplifié par l'amplificateur à fibre (26) qui agit pour annuler l'élargissement de la largeur de raie spectrale causé par la modulation de fréquence de l'EOM FM et AM combiné (42), dans lequel les crêtes de la modulation d'amplitude du faisceau de semences causée par le second signal de commande s'alignent sur les creux de la modulation de phase du faisceau de semences causée par le premier signal de commande.

2. Le système (40) selon la revendication 1, où le deuxième signal de commande (44) est une variation du premier signal de commande (44) qui a été déphasé et amplifié pour la modulation d'amplitude.

3. Le système (40) selon la revendication 1, dans lequel le premier signal de commande (44) et le second signal de commande (44) sont des signaux sinusoïdaux monotones.

4. Le système (40) selon la revendication 3, dans lequel l'amplitude du premier signal de commande (44) est choisie pour éliminer la plus grande partie de la puissance de la fréquence d'ordre zéro du faisceau de semences par l'EOM FM et AM (42).

5. Le système (40) selon la revendication 3, dans lequel l'amplitude du premier signal de commande (44) est choisie pour créer des puissances d'amplitude égale dans les fréquences d'ordre zéro et +/- premier du faisceau de semences dans les EOM FM et AM (42).

6. Le système (40) selon la revendication 5, dans lequel le premier signal d'entraînement (44) a une fréquence de 32 GHz.

7. Le système (40) selon la revendication 1, dans lequel la source optique (12) est un oscillateur maître (12).

8. Le système (40) selon la revendication 1, dans lequel le système amplificateur à fibre (40) fait partie d'un système amplificateur à fibre (50) combinant des faisceaux cohérents (CBC) ou d'un système amplificateur à fibre (70) combinant des faisceaux spectraux (SBC).

9. Le système (40) de la revendication 1, dans lequel la modulation de fréquence est fournie par l'équation:

$$E_2(t) = E_1(t)e^{i\beta f(t)}$$

dans lequel E_2 (t) est le faisceau d'amorçage modulé en fréquence généré par l'EOM AM et FM combiné (42), le faisceau d'amorçage étant défini par $E_1(t) = exp[i\phi(t)]$La fonction ϕ(t) étant imposée par l'EOM auxiliaire (16), f(t) est une fréquence du premier signal de commande RF (44), et β est une profondeur de modulation de fréquence du premier signal de commande RF (44) en radians.

10. Le système (40) selon la revendication 1, dans lequel la modulation d'amplitude est fournie par l'équation:

$$E_3(t) = \sqrt{1 - \frac{\beta}{B} f(t)}\ \ E_2(t) = \sqrt{1 - \frac{\beta}{B} f(t)}\, e^{i\beta f(t)} E_1(t)$$

dans lequel le faisceau de semences est défini par $E_1(t) = exp[i\phi(t)]E_2$ (t) est le faisceau de semences modulé en fréquence généré par l'EOM AM et FM combiné (42), dans lequel le faisceau de semences est défini par $E_1(t) = exp[i\phi(t)]$La fonction ϕ(t) étant imposée par la MOE auxiliaire (16), f(t) est une fréquence du premier signal de commande RF (44), β est une profondeur de modulation de fréquence du premier signal de commande RF (44) en radians, B est un déphasage non linéaire en radians et E_3 (t) est le faisceau d'amorçage modulé amplifié.

11. Une méthode d'amplification d'un faisceau de semences optiques, cette méthode comprenant;

modulation de fréquence du faisceau de semences, dans un modulateur électro-optique auxiliaire (EOM) (16), afin d'obtenir un élargissement de la modulation de fréquence;
moduler en fréquence le faisceau de semences en modifiant la phase du faisceau de semences en fonction du temps à l'aide d'un premier signal de commande RF (44) afin d'élargir sa largeur de raie spectrale;
moduler l'amplitude du faisceau de semences à l'aide d'un second signal de commande RF (44) de manière à faire varier la puissance du faisceau de semences dans le temps et à fournir un faisceau de semences modulé en amplitude qui est synchronisé avec le faisceau de semences modulé en fréquence, la modulation de fréquence du faisceau de semences à l'aide du premier signal de commande et la modulation d'amplitude du faisceau de semences à l'aide du second signal de commande se produisant dans une modulation de fréquence, FM, et une modulation d'amplitude, AM, EOM (42) uniques et combinées; et
amplifier le faisceau de semences modulé en fréquence et en amplitude dans un amplificateur à fibre non linéaire (28) de sorte que le faisceau de semences modulé en amplitude provoque une modulation de phase automatique dans l'amplificateur à fibre (28) qui module la phase du faisceau de semences lorsqu'il est amplifié par l'amplificateur à fibre (28) qui agit pour annuler l'élargissement de la largeur de bande spectrale causé par la modulation de fréquence de la modulation de fréquence combinée, FM, et de la modulation d'amplitude, AM, EOM (42), dans lequel les crêtes de la modulation d'amplitude du faisceau de semences causée par le second signal de commande s'alignent sur les creux de la modulation de phase du faisceau de semences causée par le premier signal de commande .

12. La méthode selon la revendication 11, dans laquelle le premier signal de commande (44) et le second signal de commande (44) sont des signaux sinusoïdaux monotones.

13. La méthode selon la revendication 12, dans laquelle l'amplitude du premier signal de commande (44) est choisie pour supprimer la plus grande partie de la puissance de la fréquence d'ordre zéro du faisceau de semences pendant la modulation de fréquence.

14. La méthode selon la revendication 12, dans laquelle l'amplitude du premier signal de commande (44) est choisie pour créer des puissances d'amplitude égale dans les fréquences d'ordre zéro et +/- premier du faisceau de semences pendant la modulation de fréquence.

15. La méthode selon la revendication 12, dans laquelle le premier signal de commande (44) a une fréquence de 32 GHz.

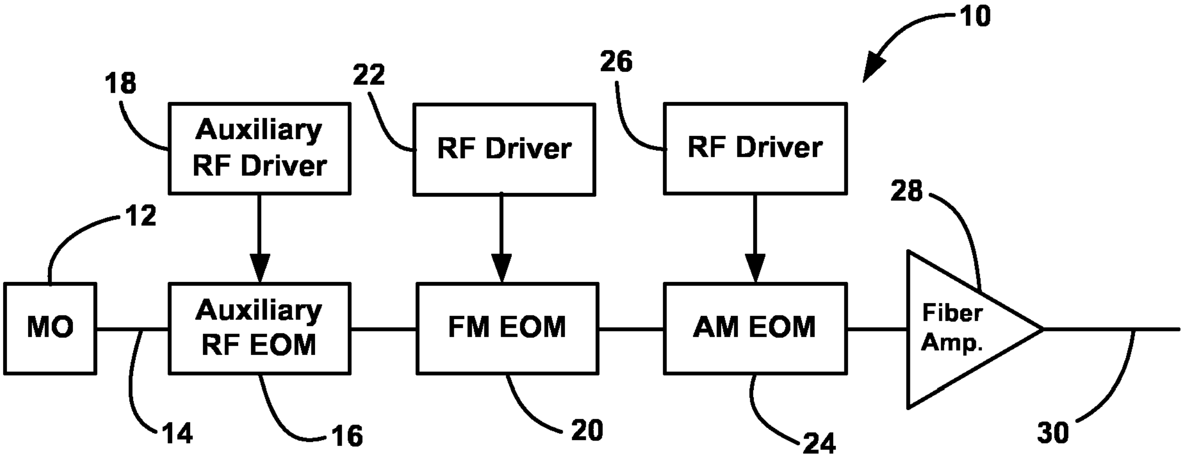


FIGURE 1

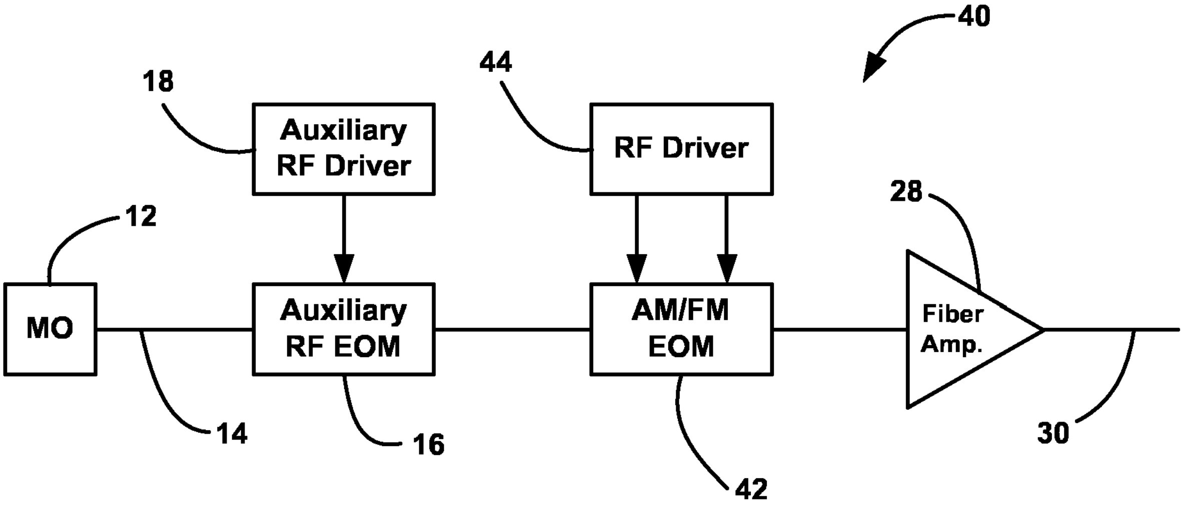


FIGURE 2

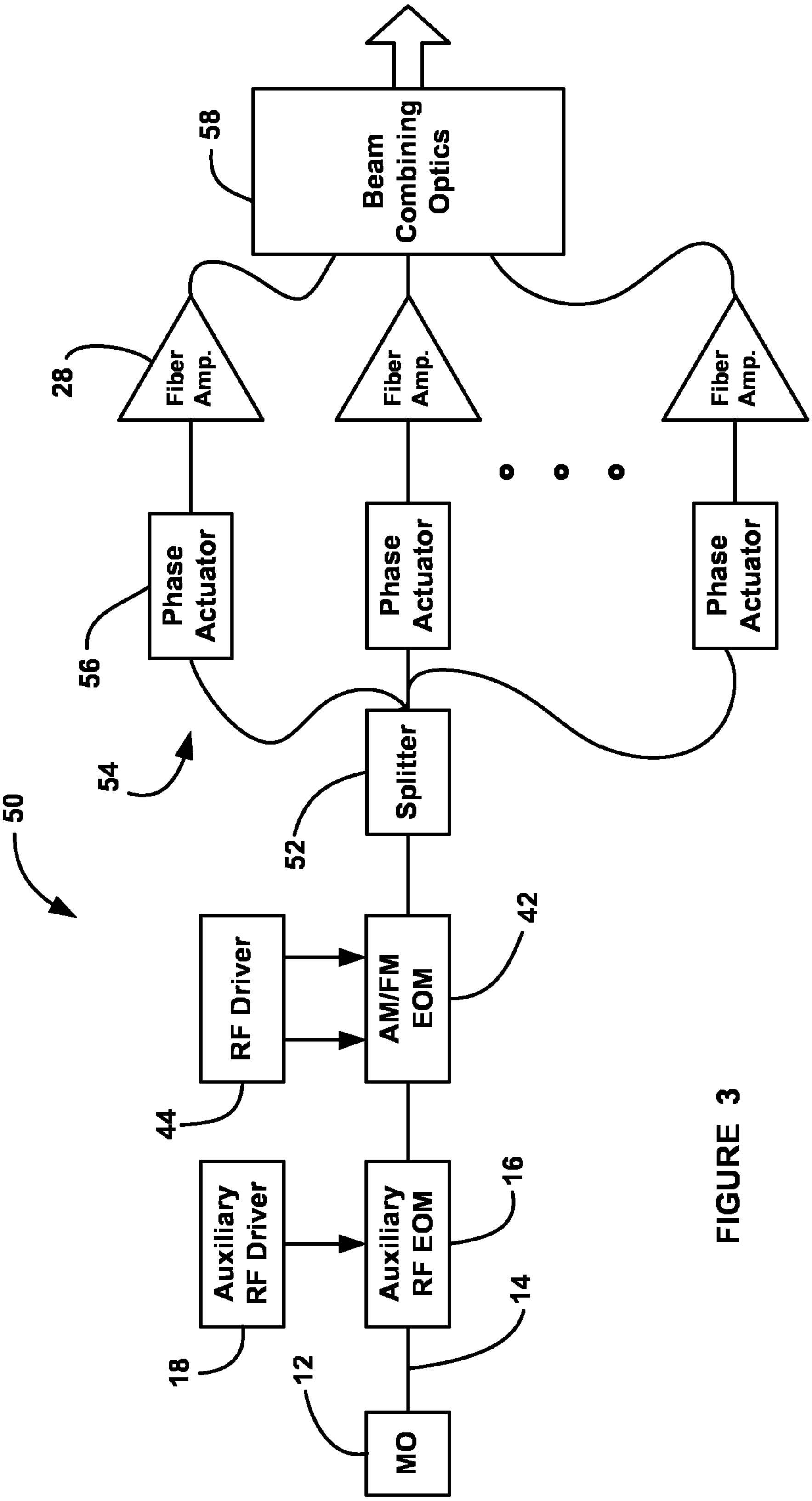
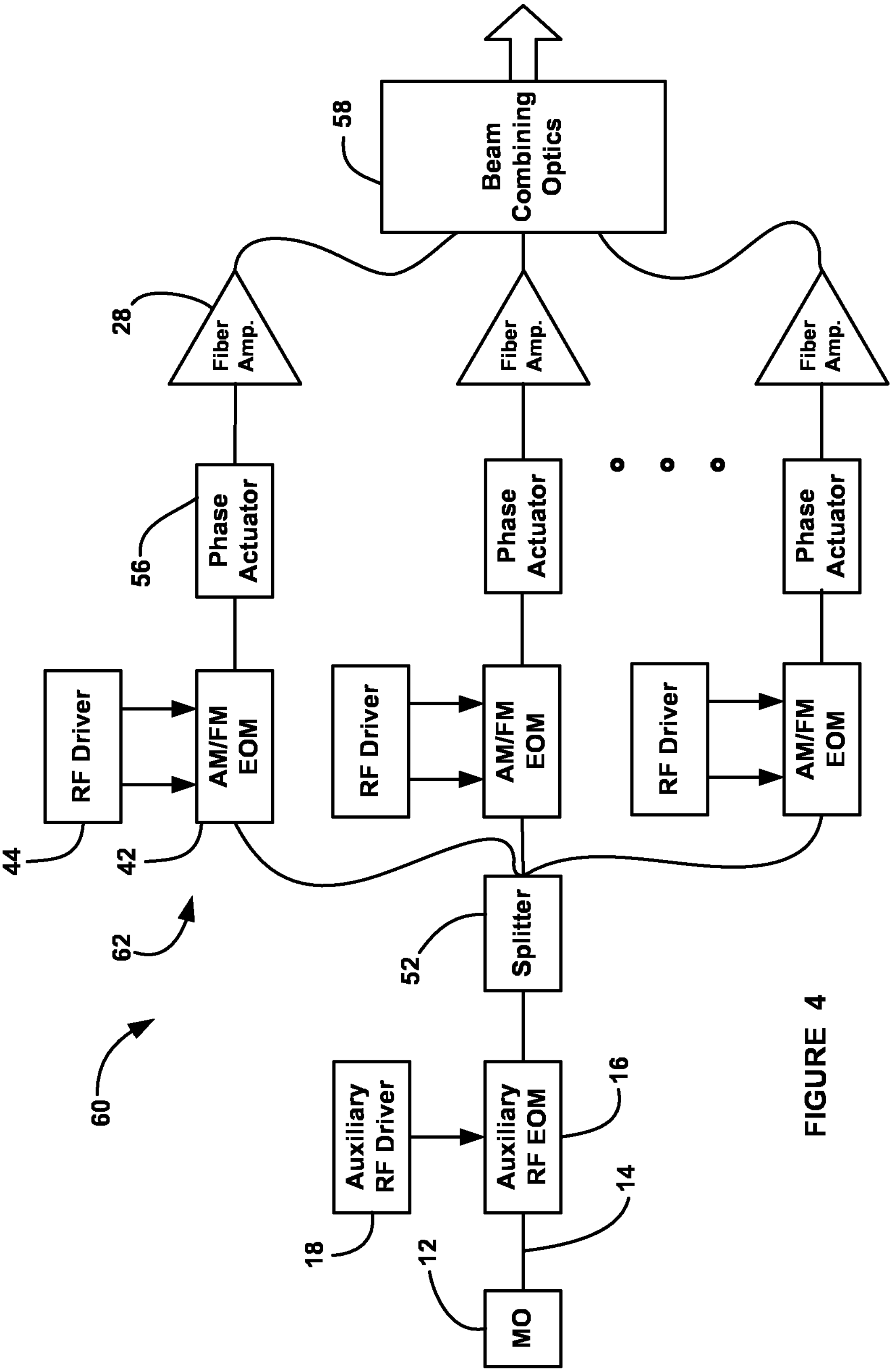

MO
12
14
Auxiliary RF EOM
16
Auxiliary RF Driver
18
AM/FM EOM
42
RF Driver
44
50
Splitter
52
54
Phase Actuator
56
Phase Actuator
Phase Actuator
Fiber Amp.
28
Fiber Amp.
Fiber Amp.
Beam Combining Optics
58

FIGURE 3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MO
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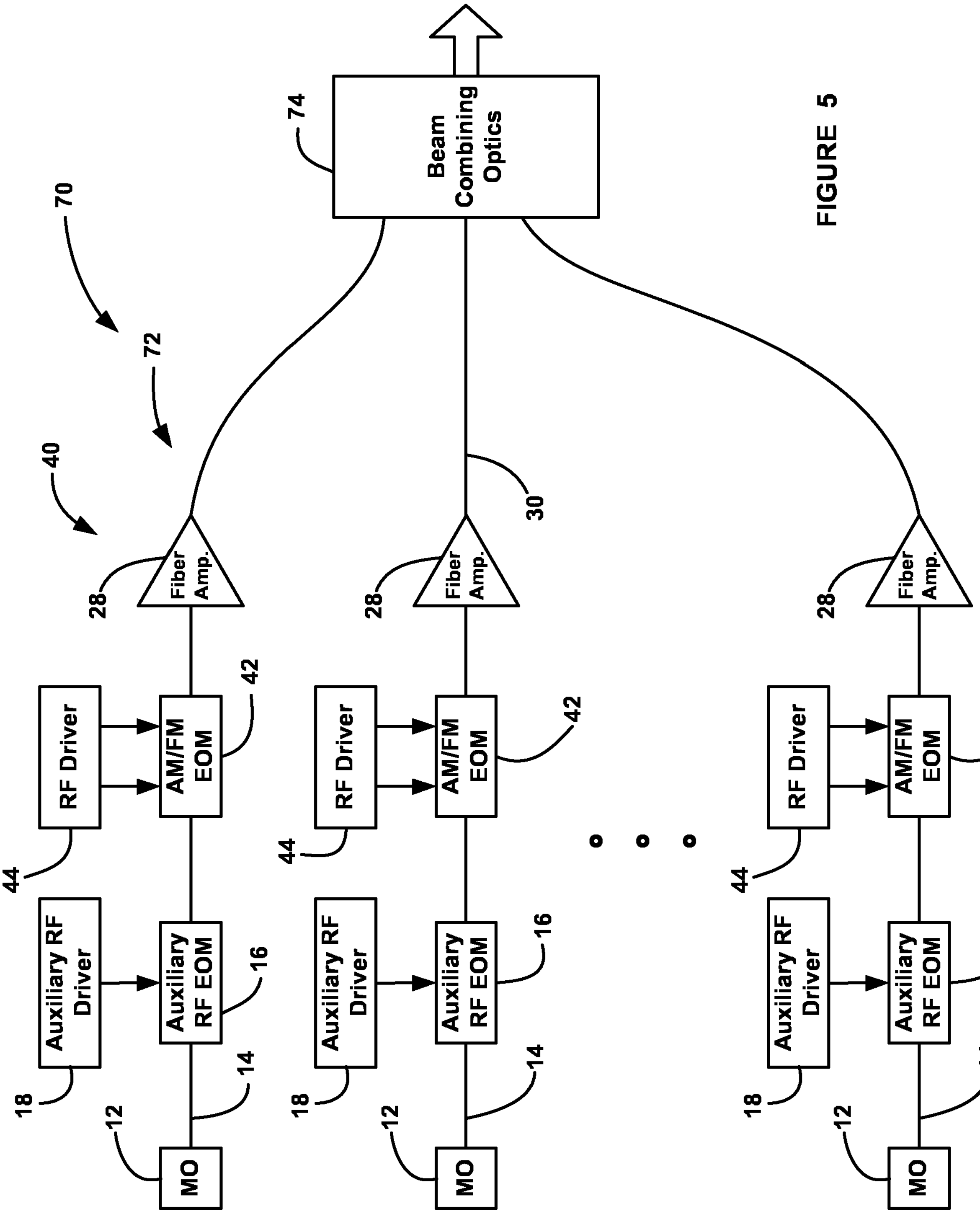
Auxiliary RF EOM
16
Auxiliary RF Driver
18
Splitter
52
AM/FM EOM
42
RF Driver
44
AM/FM EOM
RF Driver
AM/FM EOM
RF Driver
Phase Actuator
56
Phase Actuator
Phase Actuator
Fiber Amp.
28
Fiber Amp.
Fiber Amp.
Beam Combining Optics
58

FIGURE 4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72
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Beam Combining Optics
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28
Fiber Amp.
42
AM/FM EOM
44
RF Driver
16
Auxiliary RF EOM
18
Auxiliary RF Driver
14
12
MO

FIGURE 5

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

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- WO 2011053816 A1 **[0013]**
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