Multiwavelength erbium-doped fiber laser based on a nonlinear amplifying loop mirror assisted by un-pumped EDF

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Abstract: A multiwavelength erbium-doped fiber (EDF) laser based on a nonlinear amplifying loop mirror (NALM) is proposed and experimentally demonstrated. The NALM provides intensity-dependent transmissivity to equalize different-wavelength powers and the transmission can be uniquely optimized by controlling the cavity loss associated with a section of un-pumped EDF, which also enhances the output signal-to-noise ratio (SNR). Through adjusting the polarization controllers (PCs), under only 70mW pump power, up to 62-wavelength output with channel spacing of 0.45 nm has been achieved. Also, the lasing tunability and stability are verified.

OCIS codes: (140.3500) Lasers, erbium; (140.3510) Lasers, fiber; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

Over the past decade, multiwavelength fiber laser (MWFL) has attracted much research interest for its potential applications in dense-wavelength-division-multiplexing (DWDM) optical communication system, optical fiber sensor, and optical instrument testing. Generally,

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a desirable multiwavelength source needs large channel count, uniform power distribution, stable output and the wavelength spacing coinciding with ITU-T wavelength grid. Among various gain media, MWFL based on erbium-doped fiber (EDF) gets the best studied, due to its significant advantages such as narrow linewidth, high conversion efficiency, and low lasing threshold. However, at room temperature, EDF is a homogeneous broadening gain medium, which intrinsically leads to severe mode competition against stable multiwavelength oscillation. Except for the impractical cooling EDF in liquid nitrogen [1], a range of methods have been investigated to compensate this disadvantage, such as adding Raman amplifier [2], stimulated Brillion scattering gain [3], or a semiconductor optical amplifier [4] to an erbium-doped fiber laser (EDFL), inserting a frequency shifter or a phase modulator into the laser cavity [5], inducing four-wave-mixing effect [6]. Recently, two promising ways transformed from passively mode-lock fiber lasers, have been proposed to realize multiwavelength oscillation: nonlinear polarization rotation (NPR) [7, 8] and nonlinear optical loop mirror (NOLM) [9]. The two mechanisms can both induce intensity-dependent loss (IDL) to alleviate the mode competition in an EDFL, through inverting their working states from fast saturable absorbers to amplitude equalizers. However, for most reports on MWFLs, the process about how to further optimize the multiwavelength operation further on the basis of each method is usually described roughly or exhibits unremarkable effect.

In this paper, a nonlinear amplifying loop mirror (NALM), another typical saturable absorber used in pulse shaping or mode locking, is exploited for generating multiwavelength operation. Cooperative adjustments on the polarization controllers (PCs) inside and outside the NALM switch its intensity-dependent transmissivity from a fast saturable absorber to an amplitude equalizer for suppressing the mode competition in the EDFL. In contrast to use of NPR or NOLM, the NALM itself is an active component, so the laser needs no other gain media, and the lasing threshold is very low. More important, the transmission function of the NALM is associated with the gain factor G. It's well known that the lasing gain is clamped at the cavity loss in a running laser, and then inserting a section of un-pumped EDF to introduce proper additional cavity loss can improve the NALM performance indirectly for optimal multiwavelength operation. This method of optimization is a unique advantage of the NALM over NPR or NOLM. Moreover, the undesirable amplified spontaneous emission (ASE) can be absorbed by the un-pumped EDF section, which enhances the signal-to-noise ratio (SNR) of the lasing channels and assists in alleviating the mode competition either. Under only 70mW pump power, it has achieved up to 62-wavelength output within 6dB bandwidth and 51-wavelength output within 3dB bandwidth, both with 0.45nm wavelength spacing. In addition we examine the fine tunability of channel wavelength (e.g. to the ITU grid) and the overall spectral and power stability

2. Experimental setup and operation principle

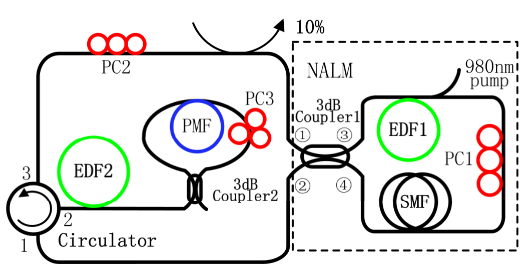

Fig. 1. Schematic of the multiwavelength EDFL based on the NALM assisted by a section of un-pumped EDF.

The setup of the MWFL is shown in Fig. 1, which resembles the "figure-eight" cavity of the classic passively mode-lock fiber laser on the whole. The right ring of the configuration inside the dash-line frame is the NALM, acting as the amplitude equalizer and gain component, composed of a 50:50 coupler (3dB coupler1), 5km single-mode fiber (SMF-28), a PC (PC1)

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with two quarter-wave plates and one half-wave plate, as well as the erbium-doped fiber amplifier (EDFA) made up of a length of 13m EDF with 100ppm erbium ion concentration, which is pumped by a 980nm laser diode with max output power of 130 mW. The left ring of the laser comprises a circulator, a PC (PC2), a 10:90 coupler that outputs 10% power from the laser cavity into an optical spectrum analyzer (OSA); and connected to the port2 of the circulator is the un-pumped EDF (EDF2) section, which is spliced with a high-birefringence Sagnec loop mirror made up of 3dB coupler2, PC3 and 9.26m polarization-maintaining fiber (PMF) with the modal birefringence of 6.5×10^{-4}.

The transmissive NALM is the key component of this MWFL. The incident field from port1 of 3dB coupler1 splits into two counterpropagating beams with equal amplitudes. In different amplification sequence through the EDFA, there is a considerable phase difference between the two beams after they propagate in the SMF and then reach 3dB coupler1 again, because the nonlinear phase shift induced in SMF depends on the beam intensity. Through the interference effect in 3dB coupler1, the transmitted and reflected powers emerge from port2 and port1, respectively. The NALM's behavior also relies on the input polarization state, controlled by PC2, and the birefringence in the loop mirror [10, 11]. And under some regular input polarization states, the NALM transmissivity can be simplified as [10–12]:

$$T = P_T / P_{in} = G(1 - 0.5\{1 + \cos[0.5(1-G) \cdot 2\pi n_2 P_{in} L / \lambda A_{eff} + \phi_d]\}) \qquad (1)$$

where, P_T and P_{in} are the respective input and transmissive powers; G is the gain factor of the EDFA; n_2 is the nonlinear index coefficient; λ is the operating wavelength; A_{eff} is the effective fiber core area and L is the SMF length. ϕ_d is the birefringence-induced phase bias controlled by PC1. In our calculation, the variation scales of λ, n_2, A_{eff} are comparatively small, treated as constants along with L, and the values are: $n_2 = 3.2 \times 10^{-20} m^2 / W$, $A_{eff} = 50 \mu m^2$, $\lambda = 1590nm$, and $L = 5km$. So the transmission is left as the function of G, P_{in}, and ϕ_d. In contrast to a passively mode-lock laser with short SMF, long SMF in use makes it possible that low-power (in the order of milliwatt) and continuous-wave (CW) light passes through the NALM. Equation (1) reveals that, with a given G factor, the monotonicity of T on P_{in} can be shifted by altering ϕ_d. In detail, for some ϕ_d set by PC1, the transmissivity increases with input power, similar to a saturable absorber, as the green lines shown in Fig. 2(a). In contrast, if ϕ_d is adjusted to other values, the working state of the NALM can be switched that the transmissivity degrades with input power, as depicted by the red lines in Fig. 2(a), so that the NALM acts as an amplitude equalizer to alleviate the mode competition in the EDFL.

In contrast to the passive mechanisms of NPR and NOLM, the NALM holds a unique feature that its transmission function has the amplification factor G. Therefore, varying G will change the amplitude and function-curve slope of T, from Eq. (1). Firstly, on the one hand, the resultant $T > 1$ presents the NALM as an active element, so the laser needs no other gain media; on the other hand, the tolerance of intensity imbalance between the input and transmissive powers of the NALM is much higher than that of NOLM, and therefore the lasing threshold of the MWFL is much lower. Secondly, if the working state of the NALM has been switched to an amplitude equalizer, the intensity-dependent curve descends more and more slowly as G decreases, as shown in Fig. 2(b). For a MWFL, too small curve slope could almost disable the amplitude equalizer; however, too large curve slope makes the transmission vary sharply with input intensity, and then the power scope that the amplitude equalizer serves is reduced, unfavorable for broad-band multiwavelength oscillation. Thus there is a moderate G value that generates the optimum multiwavelength operation without the need of changing L. In case the NALM is an independent device out of the laser, G is primarily controlled by the pump power. However, since the NALM contains the gain medium of the laser. G is

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locked to the total cavity loss instead, based on the laser principle that gain equaling to loss. As a result, tuning the total cavity loss is able to improve the NALM performance indirectly.

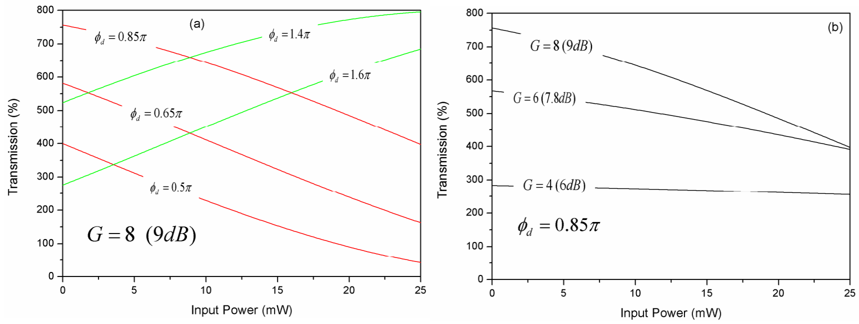

Fig. 2. Modifying the intensity-dependent transmissivity of the NALM: (a) Adjusting PC1 to switch the working state; (b) tuning the G factor to vary the transmissivity curve slope.

In the left ring of the laser, the circulator insures the unidirectional lasing oscillation and prevents residual 980nm light from injecting EDF2 via two directions. PC2 takes charge of adjusting the input polarization state into the NALM. The high-birefringence Sagnec loop mirror functions as a comb filter to select the lasing wavelengths, and the periodic reflection peaks are separated by $\Delta\lambda = \lambda^2 / (\Delta n \cdot l)$, where Δn and l are the modal birefringence and the PMF length, respectively. Moreover, the reflection profile can be finely tuned in its free-spectral range (FSR) through rotating PC3. Here, the un-pumped EDF has two smart effects: one is absorbing the undesirable ASE that deteriorates the lasing SNR and intensifies the mode competition, the principle of which is the same as the L-band EDFA that erbium ions absorb short-wavelength energy in C-band and emit long-wavelength energy in L-band [13]; the other effect of the un-pumped EDF is the very optimizing the G factor of the NALM as discussed above, because the un-pumped EDF causes net cavity loss during the process of wavelength transformation.

Alleviating the mode competition in the EDFL based on the NALM can be summarized as follows: when the working state of the NALM is switched as an amplitude equalizer by adjusting PC1 and PC2, among the initial lasing wavelengths selected by the comb filter, high-intensity ones shares less gain from the NALM than the small-intensity ones. Since the cavity loss is approximately the same for each wavelength, the negative net gain weakens the original high-intensity channel powers, until the respective gain-loss balance is achieved. And inserting a lossy EDF section into the cavity can improve the behavior of the amplitude equalizer and enhance the SNR for stable and uniform multiwavelength operation.

3. Results and discussion

In the experiment, after setting the pump power at a certain level, adjusting PC1 and PC2 by trial and error, two types of output spectra can be observed in the OSA (resolution of 0.065 nm).The one is quasi passively mode-lock state with a narrowband convex-indented spectrum and the other is typical multiwavelength oscillation that exhibits plenty of channels. When the working state of the NALM is switched to the amplitude equalizer, slightly rotate PCs again, in order to broaden the lasing-wavelength scope as well as reduce the amplitude unevenness.

At first, the EDF2 in the laser was removed, and the accumulated cavity loss is estimated to about 7.6 dB, mainly from the circulator, the PMF spliced points and the output coupler. Under 60mW pump power, a moderate result is shown in Fig. 3, with 32 wavelengths and 15dB average SNR. The adjacent channels are separated by 0.45nm, agreeing with the calculated wavelength spacing of the comb filter. As shown, the strong ASE noise beneath the multiwavelength profile results in low SNR and limits the channel count. In fact, this result suggests the NALM is not at its optimal state to suppress the mode competition in the EDFL.

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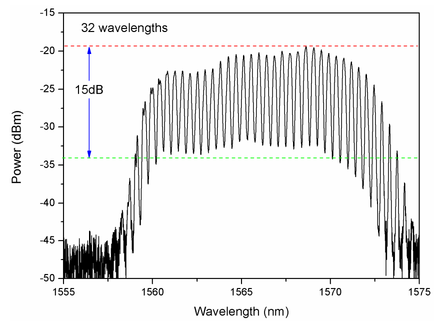

Fig. 3. Typical output spectra of the multiwavelength EDFL without un-pumped EDF under pump power of 60 mW.

As discussed in the earlier analysis, inadequate G factor in the NALM does not optimally exploit the equalization function. Since G relates to the total cavity loss in the laser, there is one more optimizing free degree for the MWFL than those based on NPR or NOLM, that is introducing proper additional insertion loss. Considering un-pumped EDF can absorb ASE and add the total cavity loss simultaneously, a section of un-pumped EDF is inserted into the cavity. With proper choice of length and doping concentration, the MWFL output improves significantly when 10m-400ppm EDF2 is in use. Along with the red shift of the lasing band, the lasing range is almost doubled and the ASE noise is also effectively suppressed that the average SNR is enhanced to 30 dB, which proves the remarkable capacity of the un-pumped EDF section. With appropriate adjustments on PCs, under only 70mW pump power, up to 62-wavelength output within 6dB bandwidth is achieved, as shown in Fig. 4(a). In general, the less lasing wavelengths, the more uniform output powers. With PCs adjusted to another combination, 52-wavelength output within 3dB bandwidth is obtained, as presented in Fig. 4(b). Thus the MWFL has the flexibility to meet different power equalized channel counts in practice. The effect of un-pumped EDF can also be explained as: only at considerable intensity imbalance between the input and transmissive ports of the NALM, can the amplitude equalizer fulfill its capacity with amplification function.

We have verified the tunability of the MWFL, which is critical for WDM applications. With the 52-wavlength output, we slightly rotate PC3 to shift the reflection profile of the high-birefringence Sagnec loop mirror in the FSR. It’s observed the lasing wavelengths can be finely tuned accordingly. Figure 5 gives the contrast results under two different PC3 states, the interleaving operation with unchanged wavelength count and spacing. If the wavelength separation is further optimized just by modifying the PMF length, it will readily meet the ITU-T grid. In the following spectral stability test of repeatedly scanning every five minutes, the power fluctuation and wavelength drift are within 1 dB and 0.08 nm, respectively, as shown in Fig. 6.

We have also checked the pump power effect on the multiwavelength oscillation. The lasing threshold is about 40 mW, for under lower pump power no stable multiwavelength output is observed. However, as long as the pump power exceeds 40 mW, a lot of lasing wavelengths arise suddenly. As the pump power increase gradually, both the powers and SNR of lasing channels grow until a stable state when the pump power reaches 70 mW. If the pump power becomes larger than 100 mW, the output degrades in terms of wavelength count and SNR. This is because the saturation effect of the ASE absorption by the un-pumped EDF with large intra-cavity power, which means tuning pump power can further optimize the multiwavelength operation. Under only 70mW pump power, this EDFL is able to sustain tens of lasing channels, which demonstrates its low-threshold characteristic over most of other reported MWFLs. Although the output power is comparatively small, it’s not a problem nowadays, with a post-EDFA in application.

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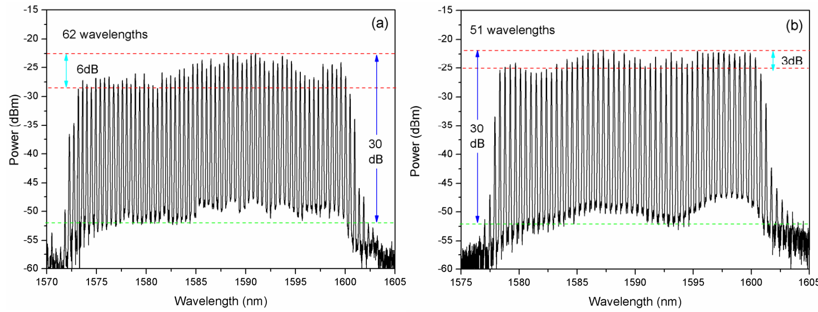

Fig. 4. Two output spectra of the MWFL based on NALM in cooperation with a section of un-pumped EDF section under 70mW pump power: (a) 62 wavelengths within 6dB bandwidth; (b) 51 wavelengths within 3dB bandwidth.

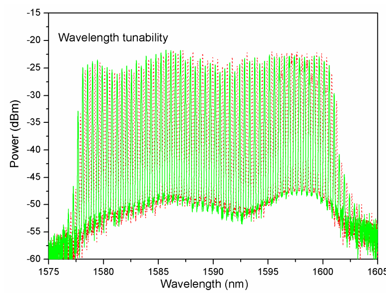

Fig. 5. The wavelength tunability of the MWFL operation with 52 wavelengths.

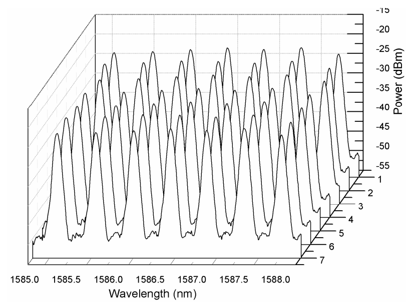

Fig. 6. The local enlargement result of repeated scanning (every 5 min) of 52-wavelength output.

4. Conclusion

We have proposed and experimentally demonstrated a stable and broadband multiwavelength EDFL based on the NALM as an amplitude equalizer, which induces intensity-dependent transmission to alleviate the mode competition in the EDFL. This MWFL has a unique approach of optimization that introducing proper cavity loss through inserting a section of un-pumped EDF to improve the NALM performance. The EDF also absorbs ASE to enhance the SNR at the same time. With appropriate adjustments on the PCs, under only 70mW pump power, up to 62-wavelength output within 6dB bandwidth and 51-wavelength output within 3dB bandwidth, have been achieved. With the tunability and stability verification, this MWFL has application prospect in DWDM optical communication system.

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