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Multiwavelength erbium-doped fiber ring laser source with a hybrid gain medium

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Abstract

Erbium-doped fiber is a gain medium exhibiting homogeneous line broadening at room temperature, while a semiconductor optical amplifier has a dominant feature of inhomogeneous line broadening. In this work, a semiconductor optical amplifier is incorporated into the cavity of an erbium-doped fiber ring laser to form a hybrid gain medium. Theoretical analysis shows that such a gain medium supports stable multi-wavelength operation. A stable 24 wavelength lasing operation with wavelength spacing of 0.5 nm and signal-to-noise ratio better than 42 dB is observed experimentally at room temperature.

Keywords: Multiwavelength; Erbium-doped fiber; Fiber Bragg grating; Semiconductor optical amplifier; Fiber laser

1. Introduction

There has been increasing research interest in multiwavelength erbium-doped fiber laser sources because of their potential applications in optical component testing, optical fiber sensor networks and dense wavelength division multiplexing (DWDM) transmission systems [1–3]. The number of wavelengths that can be generated in a fiber laser is critically important as it is directly proportional to the system transmission capacity and, in addition, a flat laser spectrum is desirable in order to obtain good system reliability. In the erbium-doped fiber laser source, however, the number of lasing wavelengths is limited by the homogeneous broadening property of erbium ions, and spectral power fluctuation also arises due to mode competition. Otherwise the erbium-doped fiber has to be cooled by liquid nitrogen at 77 K which, however, causes substantial system operation inconvenience [4,5]. Mode competition can be effectively suppressed if an inhomogeneous gain medium, such as a semiconductor laser amplifier (SOA), is employed. However, SOA possesses relatively large insertion loss and high sensitivity

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to polarization. Recently, various proposals have been made in order to achieve stable multiwavelength fiber laser operation at room temperature, including the use of a multimode fiber as a spatial mode beating filter [6], injection of Brillouin pump power [7], or incorporation of a frequency shifter into the erbium-doped fiber laser cavity [8]. Another interesting approach is the use of two SOAs in the laser cavity, to increase both the lasing bandwidth and the average power [9]. In such a system, a uniform and broadband gain spectrum can be obtained if the gain profiles of the two SOAs are carefully selected and the two gain peaks are sufficiently apart. Since semiconductor devices have a relatively high noise figure, to add an extra SOA in the laser cavity will inevitably increase the noise level. However, if an erbium-doped fiber amplifier (EDFA), instead of an SOA, is inserted into the laser cavity, the gain may be increased and its profile may be broadened while a good signal-to-noise ratio (SNR) can still be maintained.

In this paper, a multiwavelength fiber ring laser constructed by incorporating an SOA into the erbium-doped fiber ring cavity is proposed. Since SOA possesses an inhomogeneous line broadening property, a hybrid gain medium is formed in the erbium-doped fiber laser cavity and, as a result, a stable simultaneous multiwavelength laser operation at room temperature can be readily achieved and the SNR obtained is higher than that of the two SOA systems.

2. Theoretical analysis

For an EDFA, the N wavelength coupled intensity growth equation is given by [10]

$$\frac{\mathrm{d}I_i}{\mathrm{d}t} = \alpha_e I_i - \kappa \sum_{j=1}^{N} I_i I_j, \tag{1}$$

and for an SOA, it has

$$\frac{\mathrm{d}I_i}{\mathrm{d}t} = (\alpha_s - \beta I_i) I_i, \tag{2}$$

where I_i, $(i = 1, 2 \ldots, N)$ is the intensity of the ith wavelength, t is time, α_e and α_s are the overall gains for EDFA and SOA, respectively, κ and β cross and self-saturation coefficients, respectively, and are always positive. In the experimental situation, the lasing wavelength spacing of 0.5 nm is determined by the comb filter used, which is much smaller than the homogeneous bandwidth of the EDFA, but is roughly equal to the homogeneous bandwidth of the SOA. Thus, in Eqs. (1) and (2), the EDFA and SOA are considered as purely homogeneous and purely inhomogeneous gain media, respectively.

A ring laser with SOA alone as described by Eq. (2) can be solved analytically and the solution is given by

$$I_i = \frac{\alpha_s I_i(0)}{\beta I_i(0) + [\alpha_s - \beta I_i(0)]\mathrm{e}^{-\alpha_s t}}. \tag{3}$$

Eq. (3) implies that the multiwavelength operation is allowed once α_s is greater than zero. The lasing bandwidth and power can be further increased by adding an extra SOA with appropriate gain profile in the laser cavity. However, the extra SOA may degrade the output SNR because of its high noise figure [11].

For the ring laser with EDFA alone as the gain medium as described by Eq. (1), only single wavelength operation at room temperature can be supported. The solution to Eq. (1) is similar to that given by Eq. (3) except that α_s and β are replaced by α_e and κ, respectively. However, multiwavelength operation can still be observed when the erbium-doped fiber is immersed in the liquid nitrogen as the homogeneous bandwidth of EDFA is significantly reduced at low temperature.

For a fiber ring laser with both EDFA and SOA as gain elements, assuming that the system is near equilibrium, i.e., the intensity change in each of the N wavelengths per round trip in the ring cavity is small [12], the intensity growth equation for each of the N wavelengths is then

$$\frac{\mathrm{d}I_i}{\mathrm{d}t} = (\alpha - \beta I_i) I_i - \kappa \sum_{j=1}^{N} I_i I_j, \tag{4}$$

where $\alpha = \alpha_e + \alpha_s$. In general, Eq. (4) supports M wavelength operation, where $M \leqslant N$. The intensity of the M wavelength is given by $I_i = \alpha/(M\kappa + \beta)$, $i = 1, 2, \ldots, M \leqslant N$, using Gaussian elimination (see Appendix A). Linear stability analysis shows that the roots of the characteristic polynomial for the M wavelengths are $-\alpha$ and $-\alpha\beta/(M\kappa + \beta)$ with the second solution $(M - l)$ degenerating. Thus, a hybrid gain medium can support multi-wavelength operation as long as the overall gain α is larger than zero.

The above analysis shows that the incorporation of an SOA in the erbium-doped fiber ring laser cavity to form a hybrid gain medium can effectively increase the overall gain from α_e to $(\alpha_e + \alpha_s)$. The hybrid gain medium can further increase the lasing bandwidth and the power of the EDFA ring laser. In the system operation, the EDFA compensates for the cavity loss and provides a supplementary gain. Moreover, due to the self-saturation effect of SOA, the mode competition among the wavelengths can be suppressed. As a result, the operation bandwidth of the laser with a hybrid gain medium can be much broader than that of the homogeneous gain medium alone. In addition, the noise performance of a hybrid gain medium is lower than that using two SOAs because of the low noise figure of EDFA.

3. Experimental setup

The diagram of the experimental setup of the proposed erbium-doped fiber ring system is shown in Fig. 1. The main components include an EDFA, an SOA and a Mach–Zehnder interferometer. A simple explanation of the principle of system operation may be as follows:

Initially, the amplified spontaneous emission (ASE) from the SOA passes through a Mach–Zehnder interferometer which acts as a comb filter. The multiwavelength elements are subsequently amplified by the EDFA. Meanwhile, owing to the dominant homogeneous line broadening property of the erbium-doped fiber, the gain of the EDFA starts to decrease. The amplified multiwavelengths are introduced to the SOA, which is an inhomogeneous broadened gain medium. Because of the spectral hole burning effect associated with the inhomogeneous broadened gain medium, the multiwavelength elements are enhanced. After passing through the comb filter, a large portion of the multiwavelength power is reintroduced to the EDFA and is reinforced. Such a process will continue until overall gain of the hybrid medium is equal to the loss of the cavity. In this case, a stable multiwavelength laser operation can be established.

4. Experimental results and discussion

In the experimental set up as shown in Fig. 1, the EDFA used in our work consisted of a section of erbium-doped fiber of 7 m in length with an erbium concentration of 400 ppm and was pumped by the laser diode at 980 nm, with pumping power of 80 mW. The SOA was driven by a 120 mA current source. The Mach–Zehnder interferometer acted as a comb filter with a spectral peak separation of 0.5 nm. A polarization controller was placed in the ring structure to optimize the laser operation and an isolator was used to maintain the unidirectional traveling wave in the laser cavity. A 9:1 optical coupler was employed to direct the

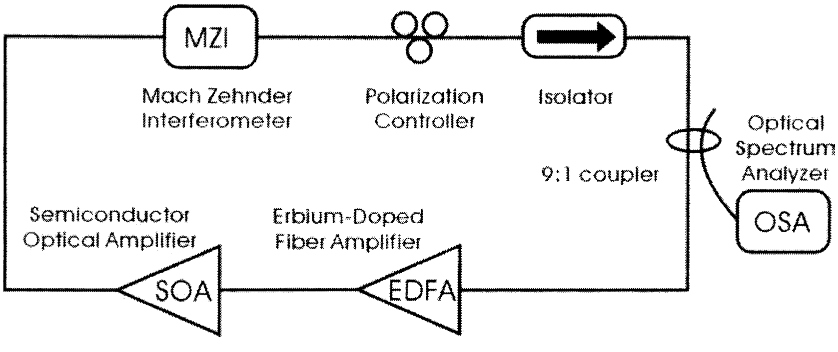

Fig. 1. Schematic of the experimental setup.

output of the ring laser to an optical spectrum analyzer (OSA) of 0.1 nm resolution. The sensitivity of the OSA was set at −50 dBm.

The system output is demonstrated in Fig. 2, where 24 lasing wavelengths with an SNR of 42 dB were observed within a 3 dB bandwidth. In fact, the gain profile of the C-band EDFA partially overlaps with the lasing bandwidth of the laser with an SOA alone, as shown in Fig. 3. The number of the lasing wavelengths can be further increased if the bandwidths of the SOA and EDFA are well overlapped.

In order to compare the characteristics of different gain media, an experiment with only an SOA incorporated into the laser ring cavity (i.e., the EDFA shown in Fig. 1 was removed) was carried out and the result is given in Fig. 3. For such a purely inhomogeneous gain medium, a simultaneous lasing of 15 wavelengths within a 3 dB bandwidth was obtained, with an SNR of 40 dB. Clearly, the number of wavelengths from such a system is considerably smaller than that from the system with a hybrid gain medium. The SNR of a single SOA system is also found to be lower than that of the system with the same SOA and an additional EDFA, which is probably due to the gain of the SOA is turned down and therefore the SOA puts out less ASE, although an extra loss is also introduced with the EDFA in the system.

The experimental system with two cascaded SOAs as the gain medium was also tested and the results obtained is shown in Fig. 4. The driving current applied to the two SOAs was 120 and 85 mA, respectively. It can be observed from Fig. 4 that about 21 wavelengths appear in a 3 dB bandwidth, with an SNR of approximately 38 dB. When compared with the single SOA gain medium, the system with two SOAs produces a larger number of lasing wavelengths but with a smaller SNR, because of the added noise figure. The laser with a hybrid gain medium has the largest SNR, which is 2 and 4 dB higher than that of the laser with single SOA and two SOAs, respectively. The lasing wavelength region is shifted in Fig. 4 due to the replacement of the EDFA with an SOA and the driving condition changes in the system.

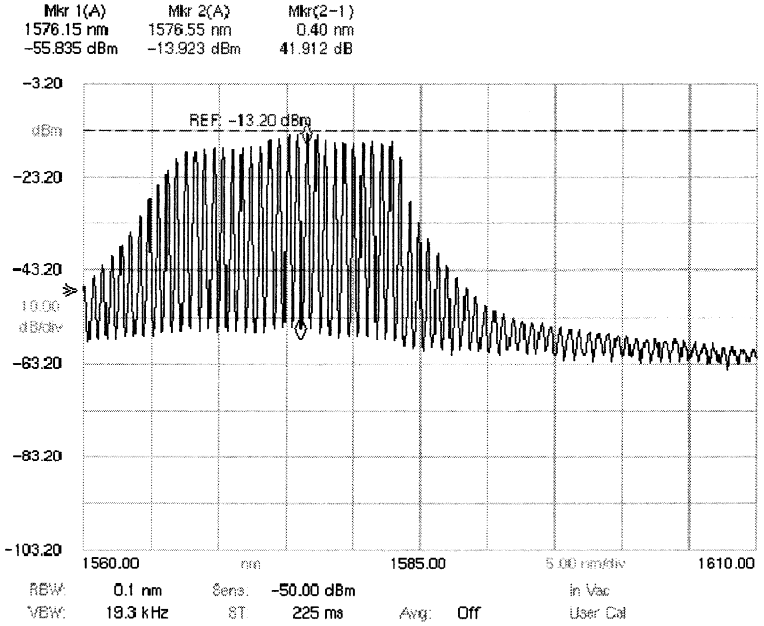

Fig. 2. Output spectrum from the fiber ring laser source with hybrid gain medium (with EDFA driving power of 80 mW and SOA driving current of 120 mA).

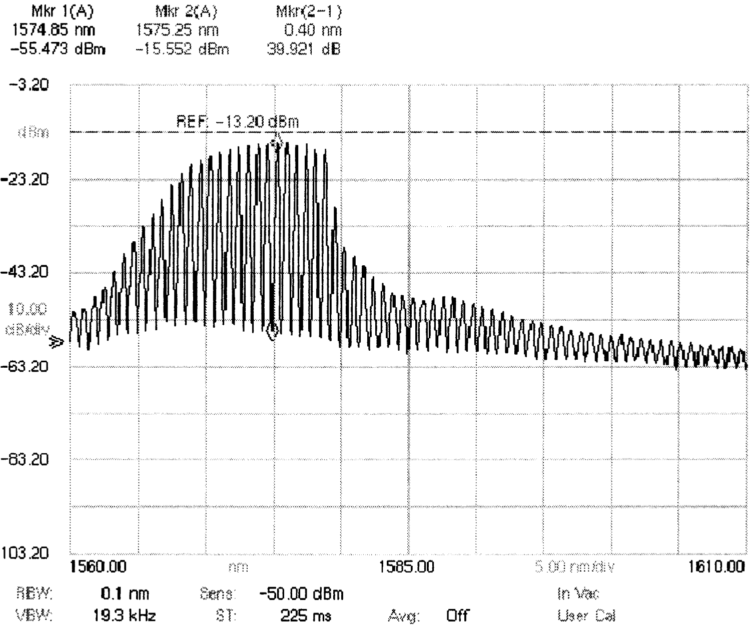

Fig. 3. Output spectrum from the fiber ring laser source with only SOA as the gain medium (SOA driving current of 120 mA).

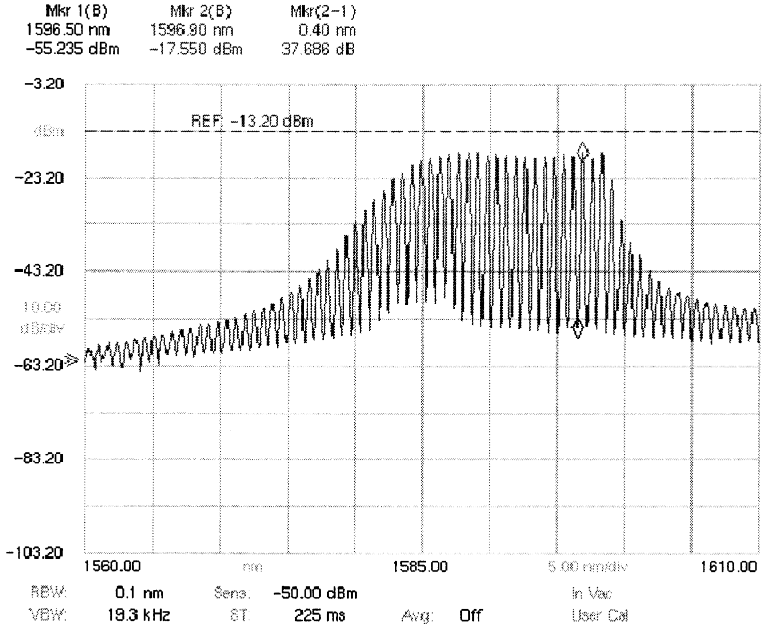

Fig. 4. Output spectrum from the fiber ring laser source with two cascaded SOAs as the gain medium (the driving current for the two SOAs is 120 and 85 mA, respectively).

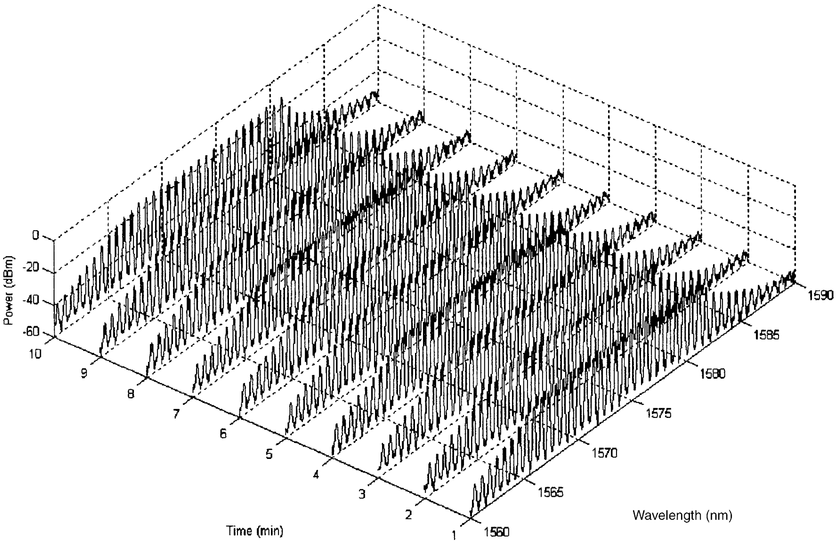

Fig. 5. Laser output spectrum scanned every 1 min.

In order to study the lasing wavelength stability at room temperature, 10 successive scans of the system output were carried out within 10 min and the results are recorded in Fig. 5. The maximum peak intensity fluctuation between the 24 wavelength lines was less than 1.5 dB.

The wavelength stability can be further enhanced by adopting a more compact and robust Mach–Zehnder interferometer, and this may be achieved by the use of feedback control in order to eliminate the drift of optical path difference in the interferometer.

5. Conclusion

A hybrid gain medium has been used in an erbium-doped fiber ring laser cavity to enable multiwave length lasing at room temperature. A stable 24 wavelengths operation at room temperature with wavelength spacing of 0.5 nm and SNR of 42 dB was achieved. The hybrid gain medium can effectively suppress the mode competition effect appearing in the laser system with EDFA while reducing the relatively large ASE noise of SOA and, as a result, the SNR improvement of 4 dB is obtained when compared with the system with two cascaded SOAs.

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Appendix A

The steady state solution of Eq. (4) with all non-zero elements can be solved by means of Gaussian elimination. By rearranging the terms in Eq. (4), we have

$$\begin{bmatrix} \kappa+\beta & \kappa & \kappa & \cdots & \kappa \\ \kappa & \kappa+\beta & \cdots & \cdots & \kappa \\ \kappa & \cdots & \kappa+\beta & \cdots & \kappa \\ \kappa & \cdots & \cdots & \cdots & \cdots \\ \kappa & \kappa & \kappa & \cdots & \kappa+\beta \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ \cdots \\ I_N \end{bmatrix} = \begin{bmatrix} \alpha \\ \alpha \\ \cdots \\ \cdots \\ \alpha \end{bmatrix}. \tag{A.1}$$

By adding every row in the matrix (A.l) and taking the sum as the first row of the matrix, we have:

$$\begin{bmatrix} N\kappa+\beta & N\kappa+\beta & N\kappa+\beta & \cdots & N\kappa+\beta \\ \kappa & \kappa+\beta & \cdots & \cdots & \kappa \\ \kappa & \cdots & \kappa+\beta & \cdots & \kappa \\ \kappa & \cdots & \cdots & \cdots & \cdots \\ \kappa & \kappa & \kappa & \cdots & \kappa+\beta \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ \cdots \\ I_N \end{bmatrix} = \begin{bmatrix} N\alpha \\ \alpha \\ \cdots \\ \cdots \\ \alpha \end{bmatrix}. \qquad (A.2)$$

The first row is now multiplied by $\frac{\kappa}{N\kappa+\beta}$, then

$$\begin{bmatrix} \kappa & \kappa & \kappa & \cdots & \kappa \\ \kappa & \kappa+\beta & \cdots & \cdots & \kappa \\ \kappa & \cdots & \kappa+\beta & \cdots & \kappa \\ \kappa & \cdots & \cdots & \cdots & \cdots \\ \kappa & \kappa & \kappa & \cdots & \kappa+\beta \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ \cdots \\ I_N \end{bmatrix} = \begin{bmatrix} \frac{N\alpha\kappa}{N\kappa+\beta} \\ \alpha \\ \cdots \\ \cdots \\ \alpha \end{bmatrix}. \qquad (A.3)$$

Starting from the second row, subtracting the first row from each row, we have:

$$\begin{bmatrix} \kappa & \kappa & \kappa & \cdots & \kappa \\ 0 & \beta & \cdots & \cdots & 0 \\ 0 & \cdots & \beta & \cdots & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & \beta \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ \cdots \\ I_N \end{bmatrix} = \begin{bmatrix} \frac{N\alpha\kappa}{N\kappa+\beta} \\ \frac{\alpha\beta}{N\kappa+\beta} \\ \cdots \\ \cdots \\ \frac{\alpha\beta}{N\kappa+\beta} \end{bmatrix}. \qquad (A.4)$$

The solution of I_i, as we stated, can be found by backward substitution.

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