Channel wavelength selectable single/dual-wavelength erbium-doped fiber ring laser

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Abstract. We present a new channel wavelength selectable single/dual-wavelength erbium-doped fiber ring laser. The novelty of this device is the use of a specially designed fiber cascaded Mach-Zender interferometer (MZI) called a channel wavelength generator (CWG) that has a triangular-shaped transfer function. The lasing wavelength only occurs in the vicinity of the peak wavelengths of the transfer function of the MZI when tuning the filter, and this makes it channel wavelength selectable. With a compound cavity structure, gain balance between two different wavelengths is easily achieved by adjusting the overlapping positions of the passbands of the filters over the CWG pattern, and as a result two stable lasing wavelengths are achieved simultaneous. Each wavelength can be tuned individually. The deviation of the exact lasing wavelength from the desired channel wavelength is estimated to be less than 1/20 of the CWG’s channel spacing (100 GHz). In addition, it is also observed that the use of the CWG reduces significantly the number of longitudinal modes, and hence improves the stability of the output power. © 2004 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1627773]

Subject terms: fiber laser; ring lasers; dual wavelength; channel wavelength selection.

Paper 030152 received Mar. 31, 2003; revised manuscript received Jun. 10, 2003; accepted for publication Jun. 10, 2003.

1 Introduction

Optical-amplifier-based ring lasers have been extensively studied in recent years with the purpose of providing a convenient, compact tunable light source for test and measurement for wavelength division multiplexing (WDM) systems, as well as being used as a stable light source for high-speed optical communication systems. Currently most of these reported ring lasers use a continuous-wavelength-tuning scheme. However, for many test or measurement applications related to a WDM system, one prefers light sources that have selectable output wavelengths within specified channel wavelengths. Such a channel wavelength selectable laser was proposed by Liou and Koren, which used a Fabry-Perot semiconductor optical amplifier as the gain medium, and an arrayed waveguide grating router (AWGR) as a channel wavelength selector. This method is straightforward and easy to implement. However, there are some drawbacks with this configuration. First, the channels available are limited to the channel number of the AWGR. Second, AWGR is usually polarization sensitive. Third, AWGR is relatively expensive. In recent years, techniques for simultaneously lasing two or more wavelengths on a single gain medium have been reported. However, this is not easy to achieve because of the cross-saturation effect of the erbium-doped fiber. Several solutions have been reported to address this problem. One approach cools the doped fiber to 77 K to reduce the homogeneous broadening effect of the fiber, and hence it reduces the cross-saturation between wavelengths. This technology is not practical for general use due to the need for extremely low temperatures. Another approach uses a compound cavity with a filter in each separate cavity. The gain control of the two lasing wavelengths is achieved with the help of either a variable coupler or two attenuators. Since fine tuning the attenuation or splitting ratio is usually difficult to achieve, it is problematic to obtain equal gains for different wavelengths.

This work suggests a new fiber ring laser structure, and to the best of our knowledge, it is the first time that the features of channel wavelength-selectivity and simultaneous two lasing wavelengths are achieved. The key component used in the proposed scheme is a specially designed cascaded all-fiber Mach-Zender interferometer (MZI) that has a triangular-shaped transfer function. We call it a channel wavelength generator or simply CWG to highlight its functions. A compound cavity similar to the works of Bakhshi and Anderson and Nilsson, Lee, and Kim is used. However, instead of using a variable coupler or attenuator, the gain balance between lasing wavelengths is achieved by adjusting the gains for each wavelength by overlapping the passband of the filter on different positions of the CWG pattern. Each wavelength can be tuned individually. Due to the triangular shape of the transfer function, the lasing wavelengths can only occur in the vicinity of the peak wavelength defined by the CWG interference pattern. In other words, by tuning the filter, the lasing wavelength changes not in a continuous way, but steps from channel to channel. The CWG can be designed and fabricated easily for any channel spacing at very low cost. Another reason for using the CWG is that it significantly reduces the bandwidth of the lasing wavelength, and hence reduces the possible longitudinal modes when compared to those where...
2 Theory

2.1 Configuration of the Laser

Figure 1 shows the configuration of the proposed wavelength selectable two-wavelength fiber ring laser. Basically, the output of an erbium-doped fiber amplifier (EDFA) is connected to its input port to construct a ring laser structure. A compound cavity is adopted with one filter in each separate cavity. The filters are used to tune the lasing wavelengths. The novel idea here is the use of a cascaded Mach-Zehnder interferometer, which is called the channel wavelength generator (CWG), to generate the desired channel wavelength passbands and to achieve equal gains between different lasing wavelengths. The linewidth of the tunable filter is selected such that each time lasing can only happen at around one of the peak channel wavelengths.

In the configuration shown in Fig. 1, the net optical gain for one roundtrip in each separate cavity is

\[
G(\lambda) = (1 - \eta) T_{MZI}(\lambda) G_{EDF}(\lambda) \exp\left(-\alpha(\lambda)L(\lambda)\right),
\]

where \(\eta\) is the output percentage of the coupler, \(T_{MZI}(\lambda)\) is the transfer function of the Mach-Zehnder interferometer, \(G_{EDF}(\lambda)\) is the EDFA gain, \(L(\lambda)\) is the length of each separate cavity, and \(\alpha(\lambda)\) is the distributed loss of all loss mechanisms for each cavity, including the insertion losses of components and the loss caused by the attenuator.

To achieve simultaneous two-lasing wavelengths, one needs,

\[
G(\lambda_1) = G(\lambda_2).
\]

2.2 Channel Wavelength Generator Design

A cascaded all-fiber Mach-Zehnder interferometer (Fig. 2) is used to generate the channel wavelength pattern. It consists of three couplers of different coupling ratios linked by two differential delays. The expression for the overall normalized bar-state output (port 1 to port 3) is

\[
T_b = c_3 c_2 c_1 \exp[i(\theta_1 + \theta_2)] - c_3 s_2 s_1 \exp[i(\theta_2 - \theta_1)]
\]

\[
- c_1 s_2 s_3 \exp[-i(\theta_2 - \theta_1)] - s_3 c_2 s_1
\]

\[
\times \exp[-i(\theta_1 + \theta_2)],
\]

where \(c_j = \sqrt{k_j}, s_j = \sqrt{1 - k_j}, j = 1, 2, 3,\) and \(k_j\) is the bar-state intensity coupling ratio of the directional couplers. \(\theta_j = \Delta L_j n \pi/\lambda, j = 1, 2, n\) is the refractive index of the fiber, and \(\Delta L_j\) is the physical length difference of the two differential delays.

If an input electric field \(E_i = [1 \ 0]^T\) is used, and we set \(\theta_2 = 2 \theta_1 + \pi/2\), the power transfer function for the bar-state output is derived from Eq. (3) as

\[
P_b = T_b^2 T_b = (c_1 c_2 c_3)^2 + (s_1 s_2 s_3)^2 + (c_1 c_2 s_3)^2
\]

\[
+ 2 c_1 s_1 c_2 s_2 (s_3^2 - c_3^2) \cos(2 \theta) + 2 c_2 s_2 c_3 s_3 (c_1^2 - s_1^2)
\]

\[
\times \cos(4 \theta) + 2 c_1 s_1 c_2 s_3 [c_1^2 \cos(6 \theta) - s_1^2 \cos(2 \theta)].
\]
Zehnder interferometer is that it gives us a more triangular-shaped transfer function (compared with the round top of a traditional fiber Mach-Zender interferometer), which allows us to achieve channel stepping with small deviations of the exact lasing wavelength from the desired channel wavelength.

3 Experiments and Discussion

The response of the designed CWG to an EDFA is examined first and shown in Fig. 3(b). The schematic diagram of the setup is shown as an inset in Fig. 3(b). In this experiment, $c_1=0.8$, $c_2=0.7$, $c_3=0.23$, and $\Delta L_f=2.035$ mm are used. A commercial EDFA, which is pumped by 980 nm and has a 1-mW output of a standard amplified spontaneous emission (ASE) spectrum is used without gain flattening.

The two-stage CWG is designed and built in-house with a 0.8-nm channel spacing. Its three couplers are fabricated on two single-mode fibers without using splicing. The required channel spacing depends on the length differences of the arms between the couplers and is obtained via two steps. First, each fiber is made roughly the designed length before making the subsequent coupler, according to the theoretical calculation. Then the small difference between the actual and calculated length differences is made up by heating and pulling one of the fibers by using the coupling machine, under the monitoring of the spectrum with an optical spectrum analyzer (OSA) and a wide-band light source. After the fiber cools down, the fiber length difference between couplers is fixed. From Fig. 3(b), it is noted that after passing through the CWG, the EDFA’s gain curve now has a periodic pattern. In the vicinity of the peak wavelengths, it has a triangular shape rather than a sinusoidal shape of a normal Mach-Zehnder interferometer. Dicon™ tunable bandpass filters with 1520- to 1570-nm tuning range and a 0.8-nm 3-dB bandwidth are then used to define the wavelength for possible lasing. However, the maximum gain is now not determined by the peak of the filter’s passband, but by the overlapping of the passband of the filter and the pattern of the CWG. This property is actually used to adjust the gain for a lasing wavelength and to achieve the gain balance between two wavelengths in the compound structure shown in Fig. 1. Figure 4(a) illustrates the principle of this operation in which the peak of the passband of the filter matches the peak wavelength of the CWG pattern in one case. The maximum gain is achieved. Then the filter is tuned slightly away from the peak wavelength and the gains become smaller. This is also experimentally demonstrated, as shown in Fig. 4(b) where the thick line corresponds to the former case and the other two thin lines correspond to the latter situations. With the dual-wavelength structure illustrated in Fig. 1, when the passband of one filter is tuned to locate one of the valleys of the CWG pattern, only one lasing wavelength is observed and it behaves like a single-wavelength laser. By tuning the other filter, the lasing wavelength changes from one channel to the other channels with a channel step of 0.8 nm specified by the CWG. The lasing wavelength can happen at all the CWG’s maxima in the range of 1520 to 1567. Figure 5 shows a portion of these available channels. However, it is noteworthy to point out that during the continuous tuning of the filter around each peak wavelength, in practice, there

Fig. 4 (a) The principle of gain adjustment. Inset: the overall transfer functions of the tunable filter and the CWG for different overlapping situations. (b) The experimental demonstration of the gain adjustment.

Fig. 5 (a) The possible lasing channel wavelengths of the proposed laser in the range given in Fig. 3(b). (b) The deviation estimation of lasing wavelength from the designed channel wavelength.
is a small range in which the lasing wavelength changes continuously. This deviation is indeed observed by tuning the filter in very small steps and recording the lasing wavelength in each step. Figure 5(b) shows the result for three channels. The largest deviation of the lasing wavelength from the channel peak wavelength is estimated to be 0.04 nm, about 1/20 of the CWG channel spacing (0.8 nm). Out of this range, no lasing wavelength can happen. This deviation is acceptable even for optical communications (according to the ITU-T grid, a deviation of 20% of the channel spacing from the nominal central frequency is acceptable). When two filters are both tuned to the vicinity of the peak wavelengths, two simultaneous lasing wavelengths are observed, as shown in Fig. 6. The equal gains between the two lasing wavelengths are obtained by slightly adjusting the passband of the filters around the peak wavelengths, as mentioned previously. Each lasing wavelength can be tuned individually in the range of 1531 to 1547 nm. The reading of the OSA for a 3-dB bandwidth is 0.015 nm when setting the resolution at 0.01 nm, which is much less than that without using the CWG. A narrower linewidth improves the stability of the output power because fewer longitudinal modes can oscillate. When the distance between the two wavelengths becomes larger, dual-wavelength simultaneous lasing can be easily achieved and long-term stable dual-wavelength output is observed. In this case, the requirement for gain balance between lasing wavelengths is greatly relaxed. In fact, even the power of each wavelength can be changed individually by varying the gain for that wavelength. The stability of the two simultaneously lasing wavelengths mainly depends on the stability of the CWG pattern, which changes very slowly due to several factors such as environment fluctuation and packaging problems. When the two lasing wavelengths are tuned quite close to each other (say, less than several nanometers), the competition between the two wavelengths becomes evident and more stringent gain balance is desired to maintain dual-wavelength output. Figure 8 shows a stable two-wavelength output when the distance between the two wavelengths is as narrow as 2.4 nm.

4 Conclusion

We demonstrate for the first time a fiber ring laser that has both the features of channel wavelength selectivity and simultaneous dual-wavelength output. The key component is a cascaded Mach-Zehnder interferometer called CWG that has a triangular-shaped transfer function around the peak wavelengths. The CWG plays three roles in the proposed scheme. First, it enables the lasing wavelength to happen only in the vicinity of the peak wavelength during continuous tuning of the filter(s). Second, it enables us to achieve the gain balance between the lasing wavelengths by simply tuning the filter. Third, it significantly reduces the number of longitudinal modes by narrowing the linewidth of the lasing wavelength and improves the output stability. A stable output of two wavelengths for as long as several hours is observed with this simple configuration. The stability mainly depends on the stability of the CWG.

References


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