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TUNABLE SINGLE-MODE SOURCE USING A COAXIALLY PACKAGED FABRY–PEROT LASER DIODE WITH A BUILT-IN EXTERNAL CAVITY

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ABSTRACT: *A tunable single-mode source is obtained using a coaxially packaged Fabry–Perot laser diode with a built-in external cavity. The facet of the coupling fiber becomes an optical reflector and forms an external cavity with a laser facet. The single-mode oscillation condition is controlled and stabilized by tuning the operating temperature. The tuning range is about 10 nm with the side mode suppression ratio of more than 27 dB when the temperature changes from 11.5°C to 25°C.* © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 48: 1991–1993, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21848

Key words: *external cavity laser; Fabry–Perot laser diode; optical communication; tunable laser diode*

1. INTRODUCTION

Tunable laser affords great flexibility and transparency in wavelength division multiplexing (WDM) optical network, and solves the inventory problem of optical transmitters. Tunable lasers are usually based on mode selection by external cavity using diffraction grating, Bragg grating, MEMS, or Fabry–Perot etalon [1]. However, these structures are limited for applications in optical networks because they are bulky and complicated to assemble various optomechanical parts. Another approach is injection locking method, in which an extra single-mode laser or a spectrum sliced broadband source is required [2, 3]. In this paper, we propose a simple tunable laser using a Fabry–Perot laser diode (FP-LD) having a built-in external cavity without any additional components. The facet of the coupling fiber becomes an optical partial reflector and forms an external cavity with laser facet. Therefore, there is no cost increment for the present conventional packaging process except nonsignificant increment of thermoelectric cooler (TEC) packaging, which is used to tune the peak wavelength. Using the proposed FP-LD, we obtained a single-mode output with the side-mode suppression ratio (SMSR) of more than 27 dB. The lasing wavelength can be tuned discretely by changing mode-matching condition of the coupled cavities.

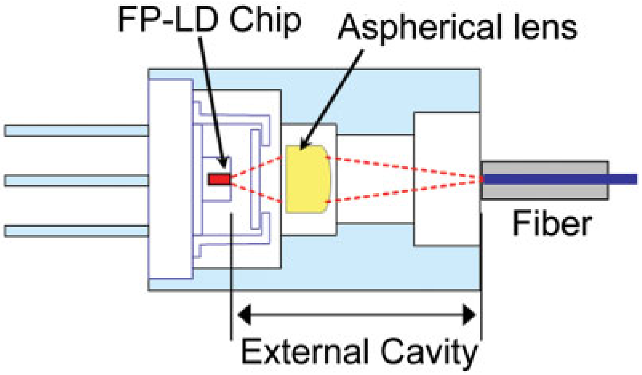

Figure 1 The cross-section of the coaxially packaged laser diode. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

2. OPERATION PRINCIPLE

In the commercial pig-tailed FP-LD, the facet of coupling fiber generally has an inclination of 6–8° in order to prevent optical feedback from the fiber. It is because the reflected light can couple with the lasing modes within the laser cavity and this coupling induces optical feedback noise [4]. However, optical feedback does not always induce noise. Proper mode matching gives line width reduction for the single-mode laser or strong side-mode suppression for the multimode laser [5–7]. The mode-matching condition is dominated by a feedback level and a relationship between an external cavity length and a laser cavity length. Thus, purposely, we eliminated an inclination from the coupling fiber and formed an external cavity between the laser diode and the coupling fiber. By adjusting the operating temperature using a TEC module, the mode-matching condition for two mode-combs of both cavities can be controlled to achieve single-mode oscillation. As the temperature of the laser diode increases, the refractive index of the active region increases. This shift leads to the change of the optical path length in the laser diode; so that, the optimal mode-matching condition for a single-mode oscillation can be obtained at a specific temperature. Moreover, many wavelengths operating in single-mode oscillation can be found by tuning the temperature, since the FP-LD inherently has multi longitudinal modes. The wavelength tuning range is restricted by the gain bandwidth of the laser diode.

3. EXPERIMENTS AND RESULTS

Figure 1 shows the cross-section of the commercial FP-LD. It has a coaxial packaging and the overall structure is not changed in this experiment. The FP-LD used in our experiment has an InGaAsP multiple quantum well structure with a maximum power of 5 mW. The length of the laser diode is about 300 μm with corresponding mode spacing of about 1.2 nm. The light from the laser diode is coupled into the optical fiber via an aspherical glass lens (ALPS™, FLAU0Z101A), which is antireflection coated for 1550 nm. The coupling efficiency is ~30% and the facet of the optical fiber is flat in order to maximize the optical feedback into the laser diode. The

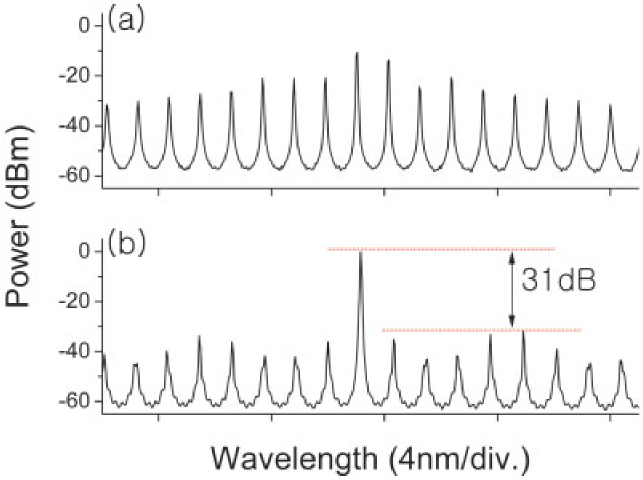

Figure 2 Optical spectra of (a) conventional FP-LD and (b) proposed FP-LD. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

coupling lens has a focal length of 0.51 mm, and the distance between the fiber and the laser diode, i.e., the external cavity length is 3.86 mm theoretically.

Figure 2 shows the measured spectra of (a) the conventional and (b) the proposed FP-LDs. In Figure 2(b), the peak wavelength of 1539.16 nm has a power of 0 dB m with 31-dB SMSR while the SMSR of the conventional FP-LD is less than 3 dB as shown in Figure 2(a). Since the single-mode condition is affected by both the bias current and the operating temperature, we fixed the bias current and varied the temperature using the external TEC. Figure 3 shows measured output optical spectra of the proposed FP-LD in single-mode oscillation at several operating temperatures. In the measured spectrum, the temperature was finely adjusted so as to match single-mode oscillation condition. When the temperature changes from the locally maximum point of SMSR, single-mode oscillation collapses and the intensity noise increases drastically due to the mode beating among many excited modes. However, if we keep on changing the temperature, the FP-LD, again, reaches the single-mode oscillation at another peak wavelength. The wavelength difference in comparison with the previous one is same as the mode spacing of the FP-LD. The peak wavelength hops successively as the temperature changes until the wavelength goes far away from the gain bandwidth of the laser diode. Then, the wavelength jumps to another lower mode within the gain bandwidth. Because the gain bandwidth of the FP-LD shifts to a longer wavelength as the operating temperature increases, the tuning range can be extended beyond the gain bandwidth.

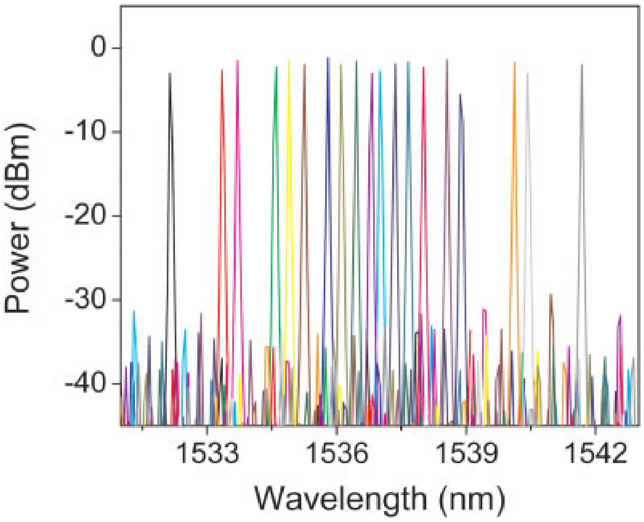

Figure 3 Measured output optical spectra of the proposed FP-LD in single mode oscillation at various operating temperatures. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

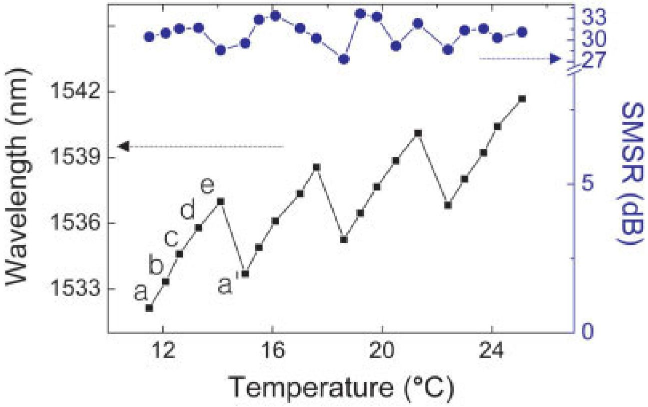

Figure 4 The peak wavelength and the SMSR at single mode operation as a function of the temperature. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

The detail tuning characteristics of the proposed laser diode are shown in Figure 4, when the temperature changes minutely from 11.5°C to 25°C. The wavelength tuning range is about 10 nm and each wavelength has an SMSR of more than 27 dB. From the starting point (a), the peak wavelength jumps to next modes (b–d) successively until the wavelength reaches point (e), and then the wavelength jumps down to point (a′). Then, the wavelength hopping repeats as the temperature increases until the wavelength gets out of the gain bandwidth. The difference between the wavelengths at (b) and (a′) is 0.36 nm, which should be equal to the longitudinal mode spacing of the external cavity. Providing that the refractive index is 1 in the optical path, we can estimate the external cavity length using the relation, $L = \lambda^2/2\,\Delta\lambda$ where L and λ are the cavity length and the wavelength of the mode, respectively. The wavelength difference ($\Delta\lambda$) is 0.36 nm and the wavelength of the mode is 1535 nm. Then the estimated value is turned out to be 3.27 mm, which is somewhat different from the theoretical value of 3.86 mm. However, it is a tolerable error coming from mispositioned LD chip because its position is rather flexible and its small variance gives large variance of the fiber position.

The modulation characteristics were investigated and the measured bit error rate (BER) curves with eye diagram are shown in Figure 5. The FP-LD was directly modulated by 155 Mbit/s pattern generator with $2^{31} - 1$ pseudorandom nonreturn-to-zero signal and the output light passed through the optical bandpass filter with 3dB bandwidth of 0.4 nm. The speed of 155 Mbit/s is rather slow for long haul transmission; however, it is enough for “fiber to the home” application, e.g., WDM passive optical network. Generally, the filtered signal from the FP-LD has strong intensity noise due to mode partition or mode fluctuation. But, in our proposed FP-LD, the eye is clearly opened as shown in the inset of Figure 5. We achieved error-free transmission over 25 km of a single-mode fiber at 155 Mbit/s with negligible power penalty in comparison with the back-to-back measurement.

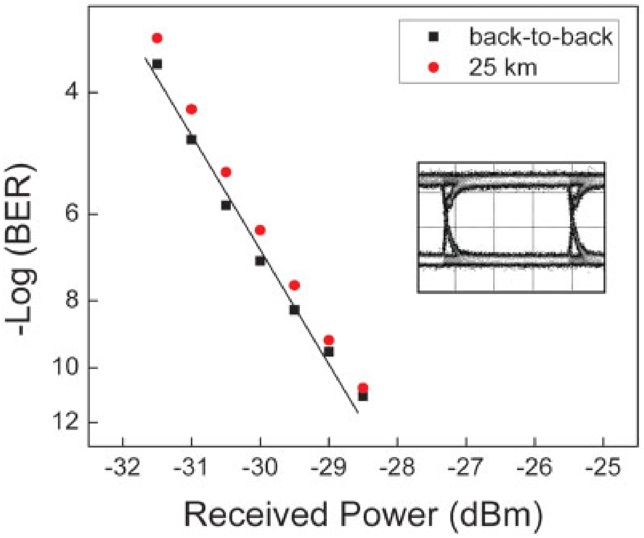

Figure 5 The measures BER curves with eye diagram at 155 Mbit/s. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

4. CONCLUSIONS

A simple and cost-effective tunable single-mode laser is proposed and experimentally demonstrated using FP-LD which inherently oscillates at multi wavelengths. As the operating temperature changes, the peak wavelength hops by an amount of FP-LD mode separation and overall tuning range is about 10 nm with side mode suppression better than 27 dB.

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DOUBLE-PASS REMOTELY PUMPED ER^{3+}-DOPED FIBER AMPLIFIER EMBEDDED WITH CHIRPED FIBER BRAGG GRATING

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ABSTRACT: *A highly efficient erbium-doped fiber amplifier configured in double-pass amplification scheme with a chirped fiber Bragg grating is demonstrated in this study. The chirped fiber Bragg grating is used to perform as the reflector and concurrently to compensate the effect of fiber dispersion. The proposed amplifier architecture is able to maintain gain of higher than 20 dB for small signals with 10 mW pump power. It has been successfully tested as the remotely pumped amplifier to compensate a span loss of 62.2 dB with 2.5 Gbps signal in a repeaterless transmission experiment.* © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 48: 1993–1996, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21847

Key words: *erbium; remotely pumped optical amplifier; double-pass; chirped fiber Bragg grating*

1. INTRODUCTION

Span engineering is very crucial in order to ensure good signal qualities in long haul-transmission systems. The limiting factors to longer reach in long-haul transmission systems are classified to attenuation, dispersion, and nonlinear effects. The first two terms are the most common issues that can be rectified with the availability of optical devices. Traditionally, the dispersion compensating modules is placed in a sandwich structure, in between two optical amplifiers [1]. On the other hand, the most notified solution to compensate both effects in a single box is discrete Raman amplifier utilizing a section of dispersion compensating fiber [2]. Even though that both effects can be resolved simultaneously, high pump power is required for this amplifier architecture. Thus, the discrete Raman amplifier is not suitable to be used as an efficient remotely pumped optical amplifier in repeaterless transmission systems. On the other hand, the remotely pumped erbium-doped fiber amplifier (R-EDFA) has been proven as the forefront candidate for this application.

The configuration of R-EDFA is mainly designed in single-pass amplification structure [3]. Since the input signal power into a remotely pumped EDFA is normally small, it can be designed to have higher operating gains. However, pump power is normally low at the location of R-EDFA. Thus, it has created a huge challenge for researchers to design an efficient R-EDFA under this restricted condition. The double-pass amplification using mirror in L-band has been proven to produce a better gain compared to its counterpart of the single-pass amplification [4]. In the report, the dispersion compensation module is located at the inline repeater not at the double-pass R-EDFA.

In this study, a new approach of integrating loss and dispersion compensating techniques into R-EDFA black box is proposed. Double-pass R-EDFA architecture with a chirped fiber Bragg