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Optically controllable dual-mode switching in single-mode Fabry-Pérot laser diode subject to one side-mode feedback and external single mode injection

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ABSTRACT

In this paper, broadly tunable dual-mode lasing system is presented and demonstrated based on single-mode Fabry-Pérot laser diode subject to the feedback of one side mode amplified by an erbium-doped fiber amplifier in the external feedback cavity. The spacing between two resonance modes in output lasing spectrum is broadly tuned by introducing differently amplified side mode into the single-mode laser via the external cavity consisted of amplifier, filter, and polarization controller so that two difference frequencies of 1 THz and 0.6 THz are given to display the tunable behavior of dual-mode emission in this work. Therefore, under an external injection mode into the laser condition, the power dependent injection locking and optical bistability of generated dual-mode emission are discussed in detail. At different wavelength detunings, the emitted two resonance modes including the dominant and feedback modes are switched to on- or off-state by selecting proper high-low power level of the external injection mode. As a consequence, the maximum value of achieved dual-mode on-off ratio is as high as up to 45 dB.

1. Introduction

All-optical switching has been received intensive attraction in technology of telecommunication networks, and has been presented and demonstrated based on various optoelectronic devices such as silicon based waveguides [1–3], semiconductor optical amplifiers (SOA) [4–6], Mach-Zehnder interferometer (MZI) configurations [7,8], nonlinear optical loop mirrors (NOLM) [9–11], photonic crystal waveguides [12–14], and semiconductor laser [15,16], in which very rich nonlinear processes such as two-photon absorption (TPA), free-carrier absorption (FCA), cross-gain modulation (XGM), cross-phase modulation (XPM), optical interferences, injection locking, and bistability are utilized to perform the all-optical switching operations. Undoubtedly, these reported switching technologies have some superior competition abilities and advantages in aspects of output power, operation speed, and power consumption, and so on. Even so, some important characteristics such as tunable wavelength range, on-off ratio of outcome signal, and low cost need significant improvements and breakings so that some novel optoelectronic devices should be proposed in order to achieve all-optical switching operation with better working performance.

In recent lasing technologies, single-mode Fabry-Pérot laser diode (SMFP-LD) that consists of a multimode laser and a built-in cavity has been demonstrated [17], and has been applied to perform various optical functions including wavelength conversion [18], photonic generation [19], modulation [20], and logic gates [21] owing to its prominent optical characteristics such as high side-mode suppression ratio (SMSR), low cost, power consumption, self-locking, low threshold, and broadly tunable range. Obviously, the SMFP-LD based applications exhibit more prominent behaviors in comparison with the cases of other semiconductor lasers. In previous report [17], it is known that the emission wavelength of dominant mode (DM) in free-running spectrum outputted from SMFP-LD can be tuned within about 10 nm wavelength range by adjusting bias current and operation temperature of active region. Here, although the widely tunable range takes on excellent features in some demonstrated technologies, broader tuning range for emission mode is strongly requested with the development of broad band optical networks and communications. Additionally, the emission wavelength of dominant mode hopes and repeats with the linear varieties of bias current and working temperature so that it is little difficult to exactly control the output wavelength of dominant mode. Therefore, in order to match the requirements of

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proposed optics technologies, a dual-mode emission system that consists of a SMFP-LD and an external feedback cavity with polarization controllers (PC), tunable filter (TF), and erbium-doped fiber amplifiers (EDFA) is presented and demonstrated in this study, in which broader tuning range for emission modes is attained, and emission mode with various wavelength can be generated, namely, the spacing between two emission modes can be quasi-continuously tuned from more than 100 GHz to about 3 THz by selecting different residual side mode as a feedback mode (FM) into the SMFP-LD [19], and the corresponding tunability is determined by the combined effects of gain bandwidths of EDFA and laser, and tunable range of filter. Of course, it is well-known that the resonance dual-mode emitted by semiconductor laser with external cavity, distributed feedback Bragg grating, or electronic negative-feedback control are successfully applied in switching [22,23], optical memory [24], millimeter-wave [25–27], terahertz signal generation [28,29], and biosensor [30]. Generally, the frequency intervals between two emission modes reported by previous studies are narrow so as to limit their applications. Surprisingly, the SMFP-LD and an external feedback cavity based dual-mode emission device remarkably increases the frequency spacing of two emission modes, and will have outstanding applications for realizing various optical functions. Hence, in this work, by utilizing the characteristics of tunable dual-mode resonance, the direct application is to perform broadband tunable dual-mode switching by introducing an external injection mode (IM) with proper power and wavelength into the SMFP-LD based device. The on- and off-state of switching can be alternatively switched by properly selecting high and low power level of injection mode based on the features of power and wavelength related injection locking and bistability. In reality, some interestingly theoretical contributions of all-optical switching have already discussed based on semiconductor laser, in which the dynamics of power and detuning dependent bistability and switching with short time caused by external injection beam are thoroughly analyzed by selecting various lasing modes [15,16,31]. Motived by these theoretical results, SMFP-LD with external feedback cavity based technology of tunable all-optical dual mode switching is presented and demonstrated under an external injection mode into the laser device condition.

2. Experimental setup and principle

The experimental setup for demonstration of all-optical dual-mode switching caused by an external injection beam into SMFP-LD with external feedback cavity configuration is shown in Fig. 1. It has already been demonstrated that only single output lasing mode as dominant mode is dominated in free-running spectrum of SMFP-LD with some special bias currents and operating temperatures, where the output dominant mode has highest peak power in comparison to other residual side modes that are sufficiently suppressed due to the strong

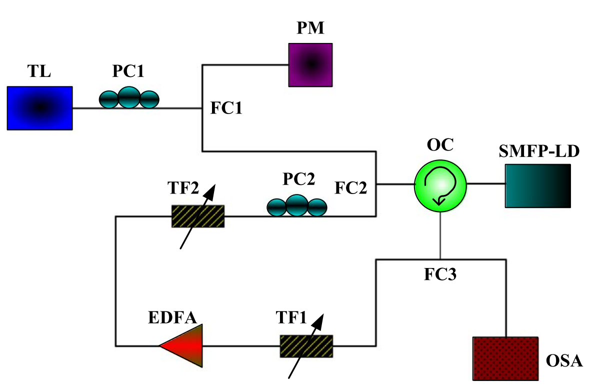

Fig. 1. Experimental setup of all-optical dual-mode switching based on SMFP-LD subject to an amplified side mode feedback and an external injection mode. Abbreviations: TL, tunable laser; PC, polarization controller; PM, power meter; FC, fiber coupler; OC, optical circulator; OSA, optical spectrum analyzer; TF, tunable filter.

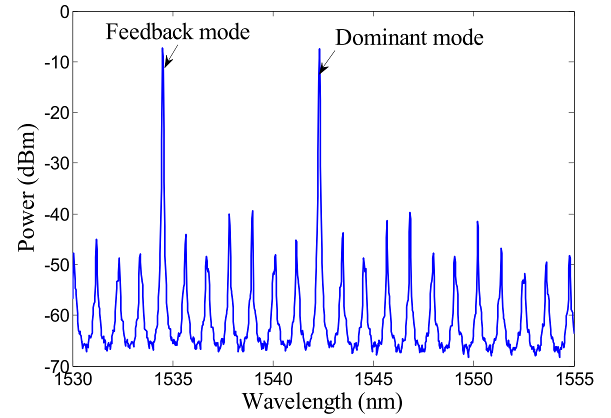

Fig. 2. Optical spectrum of dual-mode resonance.

mode competition in the laser chip [17]. Here, in order to generate dual-mode resonance, it can be seen in Fig. 1 that, after the free-running spectrum of SMFP-LD passes through the optical circulator (OC) with 3 dB loss, it is split into two branches by fiber coupler (FC3). One port is captured by the optical spectrum analyzer (OSA) to display the outcome spectrum, in which the peak for each mode and SMSR can be directly recorded, and another branch is entered into the feedback cavity containing two tunable filters (TF1 and TF2), an EDFA and a polarization controller (PC2). In the external feedback cavity, TF1 is used to let the required side mode to reach the EDFA that can boost the power of feedback side mode to an enough high level. And then, the amplified side mode orderly passes through the TF2 and PC2, in which noise generated by EDFA is thoroughly cleaned up, and the selected polarization state of feedback beam is identical to that of dominant mode (TE state). Consequently, the fed side mode with enough high power is fed into SMFP-LD via FC2 and OC, resulting in the dual-mode emission spectrum with about 33 dB SMSR shown in Fig. 2 with 27 mA bias current and 24 °C operation temperature for active region. Here, the amplified feedback mode is separated from dominant mode for ~8 nm, corresponding frequency difference of ~1 THz. Obviously, by using different side mode as the feedback injection mode, the interval of output dual-mode can be quasi-continuously varied from up to 100 GHz to about 3 THz mainly limited by the combined effects of gain bandwidth and maximum gain level of amplifier, gain bandwidth of laser, and tunable range of filter. In addition, the output two modes have very stable power level, and their power ratio can be tuned to less than 0.5 dB against increase of operation time.

In order to perform dual-mode switching process, the polarization state of an external injection beam emitted by tunable laser (TL) is still changed to TE state through PC1 for effectively performing the behavior of injection locking in laser. Output beam from PC1 is also divided into two branches by FC1 with 50/50 power coupling ratio. One branch is connected to power meter (PM) to indirectly measure external injection power for the laser, and another port with enough high power and proper wavelength is coupled into the laser through FC2 and OC to control the on- or off-state of feedback and dominant modes.

3. Results and discussion

Fig. 3 depicts the evolution of output spectrum shown on OSA as a function of wavelength detuning defined by the wavelength difference between injection mode and selected side mode. Positive (negative) wavelength detuning denotes that injection wavelength is longer (shorter) than that of selected side mode. In Fig. 3, the wavelength of side mode is 1550.2 nm, and the input power of external injection mode is set to −8 dBm level. One can see that the two resonance modes experience the change of on-off-on-state with respect to the wavelength