Demonstration of arbitrary channel selection utilizing a pulse-injected semiconductor laser with a phase-locked loop

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Abstract: An arbitrary channel selection system based on a pulse-injected semiconductor laser with a phase-locked loop (PLL) is experimentally demonstrated and characterized. Through optical injection from a tunable laser, channels formed by the frequency components of a microwave frequency comb generated in the pulse-injected semiconductor laser are individually selected and enhanced. Selections of a primary channel at the fundamental frequency of 1.2 GHz and a secondary channel in a range from 10.8 to 18 GHz are shown, where the selection is done by adjusting the injection strength from the tunable laser. Suppression ratios of 44.5 and 25.9 dB between the selected primary and secondary channels to the averaged magnitude of the unwanted channels are obtained, respectively. To show the spectral quality of the pulse-injected laser, a single sideband (SSB) phase noise of -60 dBc/kHz at an offset frequency of 25 kHz is measured. Moreover, the conversion gain between the primary and secondary channels and the crosstalk between the selected channels to the adjacent unwanted channels are also investigated. Without the need of expensive external modulators, arbitrary channel selection is realized in the proposed system where the channel spacing and selection can be continuously adjusted through tuning the controllable laser parameters.

OCIS codes: (140.5960) Semiconductor lasers; (190.3100) Instabilities and chaos; (140.3520) Lasers, injection-locked; (350.4010) Microwaves.

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1. Introduction

Radio-over-fiber (ROF) technique has been extensively investigated for its advantages of large bandwidth, low loss, and high immunity to the electromagnetic interference [1–3]. To transmit data in a multiple-users environment, photonics methods capable of selecting microwave channels with large suppression ratio to the stopband (low crosstalk), low single sideband phase noise, and wide tunability in channel selections are of great interest [4, 5]. Tunable microwave channel filters utilizing an optical phase modulator with a chirped fiber Bragg grating [6, 7], an acousto-optic superlattice modulator [8], and an intensity modulator [9, 10] have been studied. Microwave photonic filters based on circulating a cladding mode and a thermooptic switch with the ring resonators have been demonstrated [11, 12]. A technique utilizing optical heterodyne detection with a single axial mode from an injection-locked passively mode-locked semiconductor laser [13] has also been investigated. While all these techniques have been proven to be feasible, however, expensive modulators and specific narrowband resonators and gratings are needed which increase the cost and complexity of the channel selection systems.

In this paper, we propose and study an arbitrary channel selection system based on a pulse-injected semiconductor laser [14] with a phase-locked loop. With only commercially available semiconductor lasers being the active components, channel selections with large suppression ratio, wide tunability, and good spectral purity are demonstrated by utilizing the nonlinear laser dynamics with optical injection. System performances including the suppression ratios between the selected channels to the unwanted channels (crosstalk), the selection range of the channels, the spectral purity measured by the single sideband phase noise, and the conversion gain between the selected channels are experimentally characterized.

2. Experimental setup

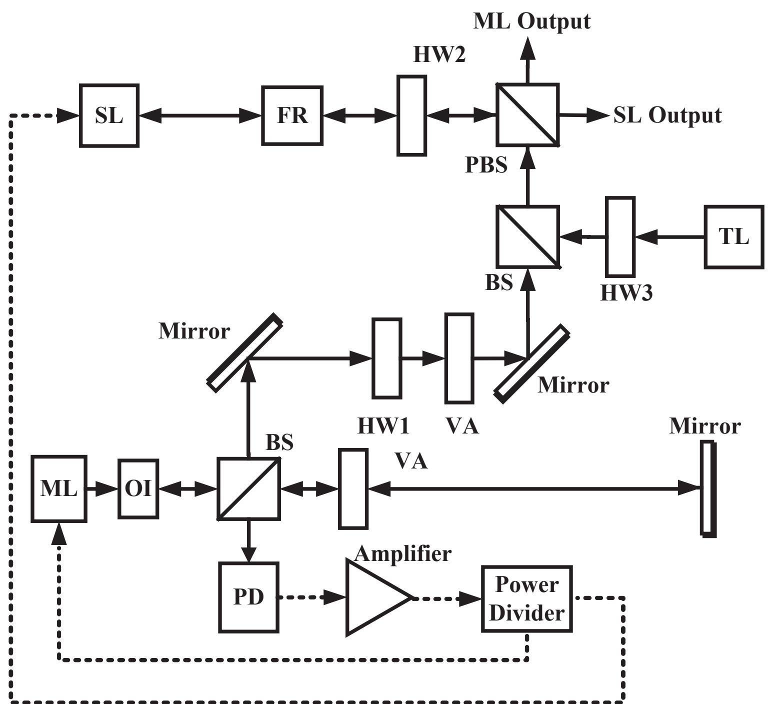

Fig. 1. Experimental setup of the arbitrary channel selection system. The slave laser (SL) is subject to an optical cw injection from the tunable laser (TL) and an optical pulse injection from the master laser with an electric phase-locked loop (PLL). PD: photodetector, OI: optical isolator, BS: beamsplitter, PBS: polarizing beamsplitter, HW: half-wave plate, VA: variable attenuator, FR: Faraday rotator, and A: amplifier. Solid and dashed lines indicate optical and electrical paths, respectively.

Figure 1 shows the experimental setup of the proposed arbitrary channel selection system. Two commercial single-mode DFB semiconductor lasers with 1.3 μm wavelength are used as the the master laser (ML) and the slave laser (SL). Both lasers emit optical power of about 8.5 mW and have relaxation oscillation frequencies of 7 GHz when biased at $J = 30$ mA deduced from their noise spectra. The ML is operated in a regular pulsing state generated by the nonlinear laser dynamics with the optoelectronic feedback scheme [15]. By adjusting the delay time t_d and the feedback strength ξ_f (the ratio of the feedback light to the ML output field) with the movable mirror and the variable attenuator, the repetition frequency f_{rep} of the regular pulsing state can be tuned in a range from 990 MHz to 2.6 GHz limited by the 3 GHz electric amplifier (JCA JCA003-201) used in our experiment. By injecting the pulses with injection strength ξ_p (the ratio of the output fields of the SL to the ML) and detuning frequency Ω_p (the difference in optical frequencies between the ML and the SL) from the ML to the SL optically, microwave frequency combs with line spacings determined by the repetition frequency f_{rep} of the regular

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pulsing states can be generated in the SL [16, 17]. To enhance and select a primary channel from the channels formed by the frequency components of the microwave frequency comb, a phase-locked loop (PLL) is arranged by applying modulation on the SL with the electric signal converted from the ML output. Further selection of a secondary channel from the high-order frequency components of the microwave frequency comb is done by optically injecting the SL with another tunable laser (TL). The ML and the SL outputs are detected by the photodetectors (Discovery Semiconductors DSC30S) and amplifiers (MITEQ AFS6-00102000-30-10P-6) with 20 GHz bandwidths and recorded with a 26.5 GHz power spectrum analyzer (Agilent E4407B).

3. Results and discussions

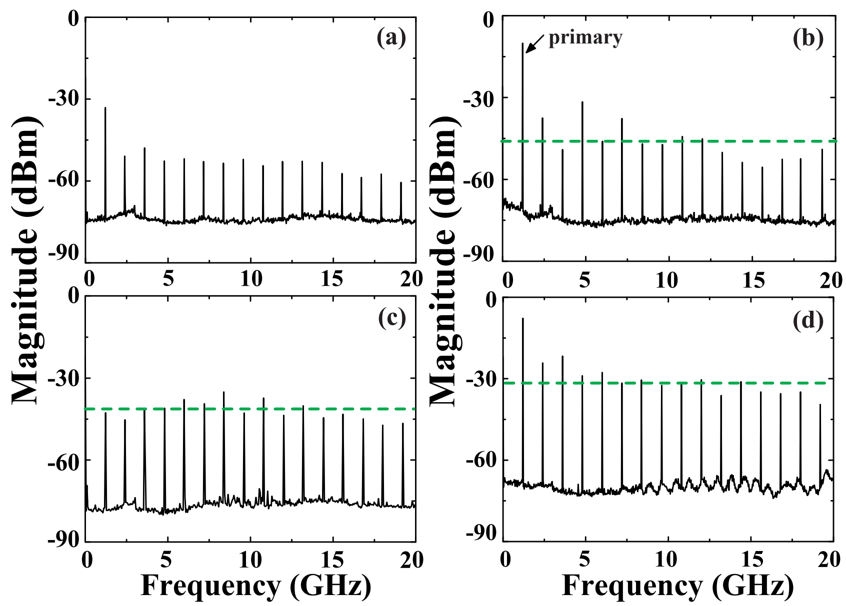

Fig. 2. (Color online) (a) Power spectrum of the ML subject to the optoelectronic feedback and the power spectra of the SL when subject to (b) both the optical pulse injection and the electric modulation from the ML output, (c) only the optical pulse injection, and (d) only the electric modulation. Dashed lines: averaged magnitude of all channels.

Figure 2(a) shows the power spectrum of the ML operating at the regular pulsing state under the optoelectronic feedback scheme with $J = 27.1$ mA, $\xi_f = 0.33$, and $t_d = 2.73$ ns. By simultaneously optically injecting and electrically modulating the pulses from the ML to the SL with $\xi_p = 0.24$ and $\Omega_p = 15.7$ GHz, a primary channel at the fundamental frequency of the microwave frequency comb is selected and enhanced at $f_{rep} = 1.2$ GHz as shown in Fig. 2(b). Suppression ratios of 41.8 dB between the primary channel to the averaged magnitude of the unwanted channels (dashed line) and 30.3 dB between the primary channel to the largest unwanted channel are obtained, respectively. Note that, the injection strength and the detuning frequency are carefully selected so that the desired primary channel can have the optimal suppression ratio. Compared to the techniques utilizing fiber Bragg gratings as the microwave photonic filters [10, 18] and that using injection locking in a Fabry-Perot semiconductor laser for single-mode selection [19] with suppression ratios of about 14-18 dB and 30 dB, respectively, the proposed pulse injection scheme shows a good quality in channel selection and filtering. As the result, with the PLL, the single channel selection (primary channel) on the SL with a large

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suppression ratio to the unwanted channels is demonstrated.

Note that, when the SL is subject to only the optical pulse injection as shown in Fig. 2(c), the primary channel at the fundamental frequency cannot be picked out in general and has a magnitude -1.5 dB lower than the averaged magnitude of the unwanted channels. On the other hand, when the SL is subject to only the electric pulse modulation as shown in Fig. 2(d), the magnitude of the primary channel is only 21.1 dB higher than the averaged magnitude of the unwanted channel. Moreover, selection of a secondary channel at a high-order frequency component will not be possible due to the limited bandwidth of the electric loop. Without the contribution from the optical path, spurious noise on the noise floor seen between the frequency components generated from the residuals of the loop frequency from the feedback delay loop is notable and which is difficult to be eliminated.

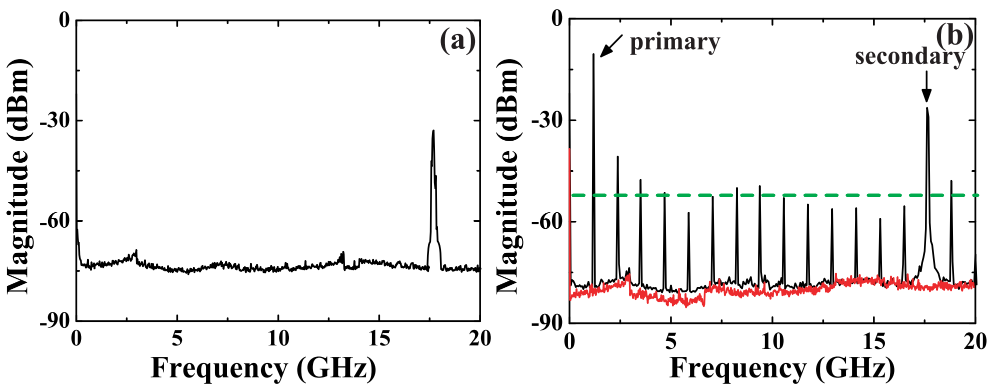

Fig. 3. (Color online) (a) Power spectrum of the P1 state of the SL subject to the optical injection from the TL. (b) Power spectrum of the SL subject to both the pulse injection with PLL from the ML and the optical injection from the TL. The P1 frequency of 18 GHz matches exactly with the frequency of the 15^{th} channel. Dashed lines: averaged magnitude of all channels. Red curve: background level.

To further select a secondary channel from one of the high-order components of the microwave frequency comb, another tunable laser (TL) is used for injecting the SL. When only injected with the TL, the SL can be driven into a period-one (P1) oscillation state [20, 21] by properly adjusting the injection strength ξ_t (the ratio of the output fields of the TL to the SL) and the detuning frequency Ω_t (the difference in optical frequencies between the TL and the SL). The oscillation frequency of the P1 state can be easily tuned in a wide range continuously by changing ξ_t. Figure 3(a) shows the power spectrum of the P1 state with an oscillation frequency of 18 GHz obtained with $\xi_t = 0.41$ and $\Omega_t = 17.3$ GHz. As shown in Fig. 3(b), by applying the optical injection from the TL to the before-mentioned pulse-injected SL with the PLL, a secondary channel (the 15^{th} channel) determined by the oscillation frequency of the P1 state is picked out from the high-order components of the microwave frequency comb. Suppression ratios of 44.5 and 25.9 dB between the primary and secondary channels to the averaged magnitude of the unwanted channels and 29.8 and 21.5 dB between the primary and secondary channels to their adjacent channels are demonstrated, respectively. By varying the injection strength ξ_t from the TL, thus the P1 oscillation frequency, different channels of the microwave frequency comb seen in Fig. 2(b) can be individually selected.

Figure 4 shows the injection strength ξ_t required for selecting different channels from the microwave frequency comb. By properly adjusting ξ_t, P1 states with different oscillation frequencies can be generated. When the oscillation frequency of the P1 state coincides with the frequency of a component of the microwave frequency comb, or a channel, such particular

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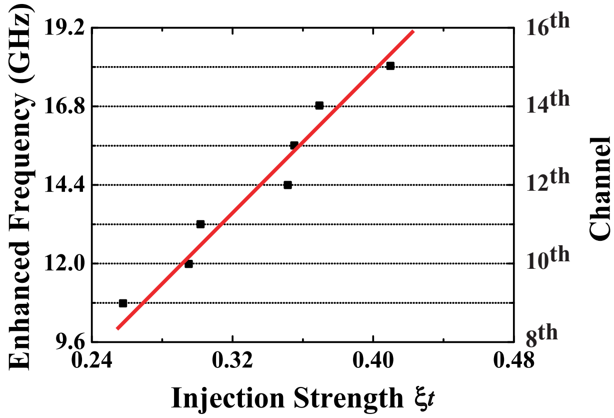

Fig. 4. (Color online) Linear tunability between the selected frequency (channel) and the injection strength ξ_t.

channel can be individually selected and enhanced. A selection range of 7.2 GHz from the 9^{th} to the 15^{th} channel (corresponding to 10.8 to 18 GHz) is obtained, which is bounded by the laser relaxation oscillation frequency and the 20 GHz bandwidths of the photodetector and power amplifier used.

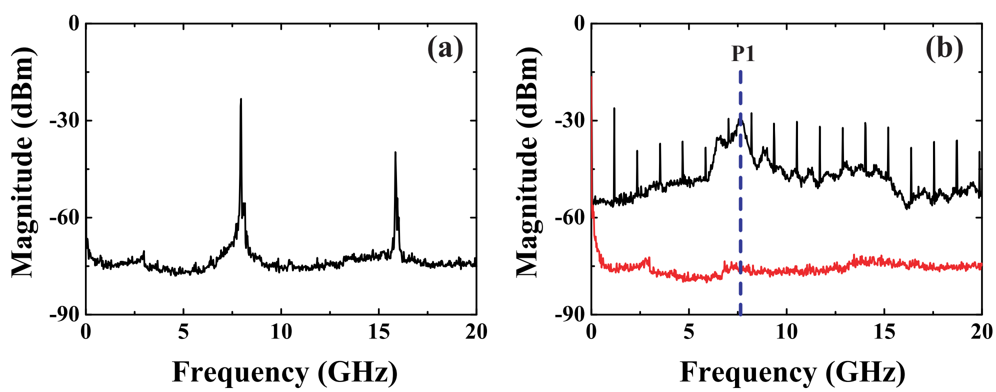

Fig. 5. (Color online) (a) Power spectrum of the P1 state of the SL subject to the optical injection from the TL. (b) Power spectrum of the SL subject to both the pulse injection with PLL from the ML and the optical injection from the TL. The P1 state has an oscillation frequency of 7.2 GHz detuned from the channels. Red curve: background level.

Note that, careful adjustment of ξ_t (within about $\pm 5\%$) is needed when selecting the secondary channel. If the oscillation frequency of the P1 state generated does not match with the frequency of one of the channels, the laser could be driven into unstable oscillations. Figure 5(b) shows the power spectrum obtained when the oscillation frequency of the P1 state (7.9 GHz as shown in Fig. 5(a)) is detuned from the channels. Compared to the stably phase-locked condition where the frequency of the P1 state matches exactly with the frequency of one of the channels (as shown in Fig. 3(b)), the SL becomes unstable and the spectral floor is lifted substantially higher compared to the background (red curve). Nonetheless, a locking range of around 510 MHz is achieved in the system when the P1 frequency is detuned away from a selected channel.

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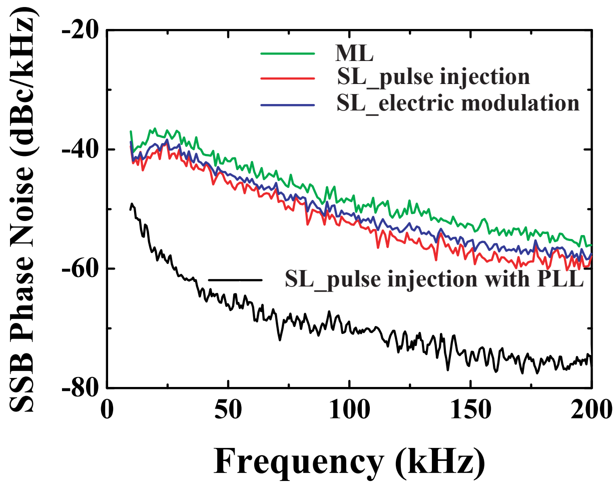

Fig. 6. (Color online) SSB phase noise of the primarary channel (1^{st} channel) of the ML (green), the pulse-injected SL with PLL (black), the SL with only the optical pulse injection (red), and the SL with only the electric modulation (blue), respectively.

The single sideband (SSB) phase noise of the system is measured to examine the spectral purity of the channel selected. Figure 6 shows the SSB phase noise of the primary channel (1^{st} channel) from the spectra of the ML (green), the pulse-injected SL with PLL (black), the SL with only the optical pulse injection (red), and the SL with only the electric modulation (blue)) as seen in Figs. 2(a)–2(d), respectively. As shown, a SSB phase noise of -60 dBc/kHz (equivalent to -90 dBc/Hz) is achieved at an offset frequency of 200 kHz for the ML, the SL with only the optical pulse injection, and the SL with only the electric modulation. On the contrary, the pulse-injected SL with the PLL reaches -60 dBc/kHz at only 25 kHz. Clearly, the spectral quality of the selected channel is significantly improved when the PPL is applied, where about 20 dB suppression in the SSB phase noise is observed. Compared to the harmonic frequency-locked states in a negative optoelectronic feedback laser (SSB phase noise of about -83 dBc/Hz offset at 200 kHz) [22] and the optical frequency comb generated with the opto-electronic oscillator using phase modulator (SSB phase noise of about -95 dBc/Hz offset at 200 kHz) [23], the pulse-injected SL with the PLL (SSB phase noise of about -105 dBc/Hz offset at 200 kHz) shows excellent quality in the spectral purity.

To further investigate the performance of the system in communications, conversion gain from the primary channel to the secondary channel is examined and analyzed [24]. A microwave signal at 1.2 GHz with a power of 0 dBm is directly modulated on the SL at the primary channel, where Fig. 7(a) shows the power spectra of the SL with (black curve) and without (green curve) the modulation, respectively.

By calculating the differences between the spectral peaks with and without the modulation for each channel, the conversion gain of each channel is obtained. As shown in Fig. 7(b), the conversion gains of the primary and the secondary channels are about 11.4 and 11.0 dB, respectively, while the averaged conversion gain of the unwanted channels is about 4.9 dB only indicated by the dashed line. As can be seen, the primary and secondary channels with larger magnitudes successfully gain more power compared to the unwanted channels mainly due to the gain competition process. Moreover, the suppression ratios between the primary and secondary channels to their adjacent unwanted channels (crosstalk) are further improved to 34.3 and 30.6 dB, respectively, which are slightly better than the suppression ratios obtained from

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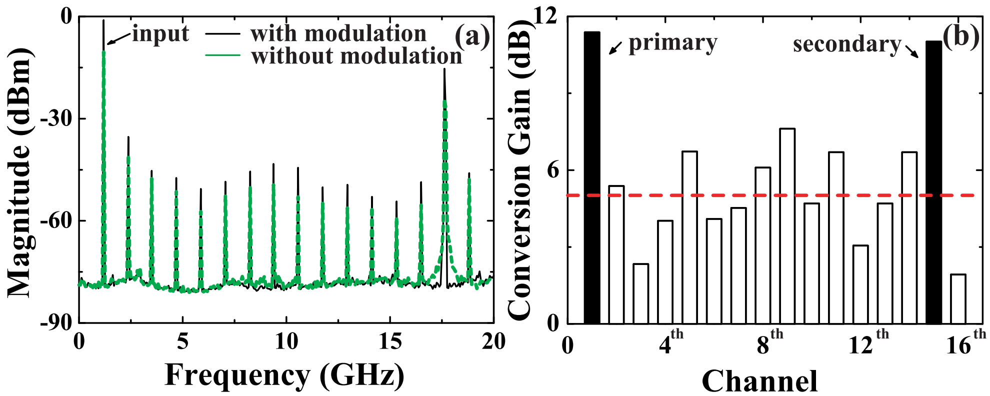

Fig. 7. (Color online) (a) Power spectrum of the SL with (black curve) and without (green curve) modulation. (b) Conversion gain for each channel. Dashed line: average conversion gain of the unwanted channels.

a tunable ring resonators with about 30 and 24 dB for the two selected channels [11]. Similar results in the conversion gain are observed when the modulation is applied on the secondary channel.

4. Conclusions

In conclusion, we have experimentally demonstrated and characterized the proposed arbitrary channel selection system utilizing a pulse-injected semiconductor laser with the PLL. Simultaneous selection of a primary channel and a secondary channel is realized, where a selection range of about 7.2 GHz for the secondary channel is obtained. Suppression ratios of 44.5 and 25.9 dB between the primary and the secondary channels to the averaged magnitude of the unwanted channels are achieved, respectively. A SSB phase noise of -60 dBc/kHz is reached for the primary channel at an offset frequency of 25 kHz, which is about 20 dB lower than the SSB phase noise obtained in the ML and the SL with only the optical pulse injection or the electric modulation. By modulating the SL at the frequency of the primary channel directly, conversion gains of 11.4 and 11.0 dB on the primary and the secondary channels are found while suppressions of more than 30.6 dB between the selected channels to their adjacent unwanted channels are achieved. Without the need of the expensive external modulators or narrowband filtering components, the proposed scheme demonstrate an alternative configuration for channel selection which the channel spacing and selection can be continuously adjusted through tuning the controllable laser parameters.

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