# Demonstration of Arbitrary Channel Selection Utilizing a Pulse-Injected Double Phase-Locked Semiconductor Laser

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## ABSTRACT

We demonstrate and characterize arbitrary channel selection utilizing both the double phase-locked and optical injection schemes experimentally. The double phase-locked scheme is realized by both optical injection and electrical modulation to the slave laser (SL) from a pulsed laser. The pulsed laser is generated by the semiconductor laser under optoelectronic feedback, which outputs repetitive pulse train with the repetition frequency controlled by the feedback delay time and feedback strength. When the SL subject to only the optical pulse injection from the pulsed laser, a broadband microwave frequency comb with amplitude variation ±5 dB in a 20 GHz range is generated. By further applying an electrical modulation to form a double phase-locked condition, a main channel can be selected accordingly. The advantages of large channel suppression ratio, system stabilization, and spurious noise reduction are obtained by using the double phase-locked technique. Moreover, by further applying an optical cw injection from a tunable laser, we demonstrate the selection of a secondary channel. A selection range of about 7.2 GHz is achieved by adjusting the cw injection strength. Average channel suppression between the main and secondary channels to the undesired channels with ratios of 41.8 and 25.9 dB are obtained, respectively. The single sideband (SSB) phase noise of -60 dBc/kHz (-90 dBc/Hz estimated) is achieved at offset frequencies of 25 and 200 kHz for the main and secondary channels, respectively. Demonstration of communication between the main and secondary channels is also demonstrated.

**Keywords:** semiconductor lasers, nonlinear dynamics, optical injection

## 1. INTRODUCTION

Due to the increasing demand of high speed, large traffic capacity, and long distance of data transmission, radio-over-fiber (RoF) system[1] is commonly adopted to fully take the advantages of light, such as large bandwidth, low transmission loss, and immunity to electromagnetic interference. After transmission to the base station through optical fiber, the microwave signal processing of channel selection is demanded for indoor communication to overcome the many-users requirement. Hence, narrow-band microwave channel selection schemes utilizing optical methods have been an active research field recently.[2,3] The important characteristics for channel selecting performance are the channel crosstalk, tunability, and suppression ratio to the stopband. The microwave signal selection with performance of spectral purity deduced from the low single sideband (SSB) noise and the large channel suppression ratio relative to the undesired channels is highly desirable.

Several optical approaches for microwave channel selection have been reported in the past decade. Techniques based on the fiber Bragg grating incorporating with an optical phase modulator,[4,5] acousto-optic superlattice modulator,[6] and intensity modulator[7,8] have been demonstrated, where the tunable microwave selection can be achieved. Demonstration of microwave channel selecting using the fiber ring resonators have been shown which can also provide the capability of wavelength selection and tuning.[9,10] By utilizing three-dimensional woodpile photonic crystals and working on the basis of resonant coupling between the x-type waveguide and acceptor-type cavity, the three-port channel dropping has been reported.[11] Other technique utilizing optical heterodyne detection by a single axial mode from an injection-locked passively mode-locked semiconductor laser has also been investigated.[12] However, external intensity modulator, phase modulators, specific narrowband fiber Bragg

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Physics and Simulation of Optoelectronic Devices XIX, edited by Bernd Witzigmann, Fritz Henneberger, Yasuhiko Arakawa, Alexandre Freundlich, Proc. of SPIE Vol. 7933, 793322 · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.873719

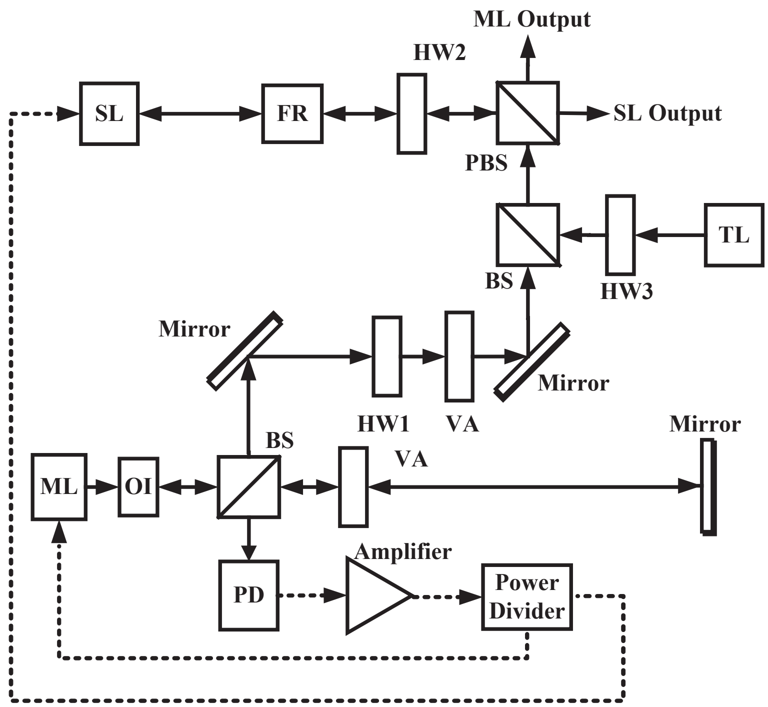


**Figure 1.** Experimental setup of the arbitrary channel selection system. The slave laser (SL) is subject to an optical injection from a tunable laser (TL) and double phased-locked loops (PLL) from the master laser with both optical injection and electric modulation. PD: photodetector, OI: optical 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.

grating, or radio frequency signal generator are required in the above-mentioned schemes, which increased the cost and complexity of the system.

In this paper, we demonstrate the arbitrary channel selection based on a double phase-locked microwave frequency comb with external optical injection. Without the need of expensive intensity modulator, phase modulator, acousto-optic modulator, RF signal generator, or fiber ring resonator, channel selection with large suppression ratio to the undesired channels and good spectral purity is demonstrated utilizing the nonlinear dynamics of the semiconductor laser.[13,14] The single sideband (SSB) noise and tunability are measured to examined the system feasibility. Moreover, the proof of concept experiment of channel communication between the selected channels is also carried out.

## 2. EXPERIMENT SETUP

Figure 1 shows the schematic setup of the arbitrary channel selection system. Two commercial single-mode DFB semiconductor lasers are used as master and slave lasers. Both lasers emit optical power of about 8.5 mW with 1.3 $\mu$m wavelength and have relaxation oscillation frequencies of 7 GHz when biased at $J = 30$ mA. The slave laser (SL) is double phase-locked by both optical injection and electric modulation from a pulsed master laser (ML). The master laser is operated in the regular pulsing states with an optoelectronic feedback configuration.[15,16] By adjusting the delay time $t_d$ and the feedback strength $\xi_f$ (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 of 990 MHz to 2.6 GHz. The tuning range is mainly limited by the 3 GHz electric amplifier (JCA JCA003-201) used in our experiment. A phase-locked loop is formed by optically injecting the SL from the ML through a free space circulator, which consists of the half-wave plates, the polarizing beam splitter, and the Faraday rotator. The SL can be driven into various rich dynamical states by adjusting the operational parameters such as the bias current $J$ of the SL, the normalized injection strength $\xi_p$ (the ratio of the output fields of the SL to the ML), and the detuning frequency $\Omega_p$ (the difference in optical frequencies between the ML and the SL). The other phase-locked loop is formed by applying the electric modulation on the SL converted from the ML output. Channel selection with high stability and large suppression ratio is achieved by applying the double phase-locked loops on the SL.

Moreover, with proper injection from another tunable laser (TL), the SL can be driven into the period-one (P1) state.[17,18] By properly selecting the detuning frequency $\Omega_t$ (the difference in optical frequencies between the TL and the SL), the oscillation frequency of the P1 state can be tuned. The oscillation frequency is proportional to the optical injection strength applied. Therefore, by combining the P1 state to the already phase-locked system, a secondary channel can be selected where its frequency is determined by the injection strength $\xi_t$ (the ratio of the output fields of the TL to the SL). The output signals of the ML and the SL are detected by 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

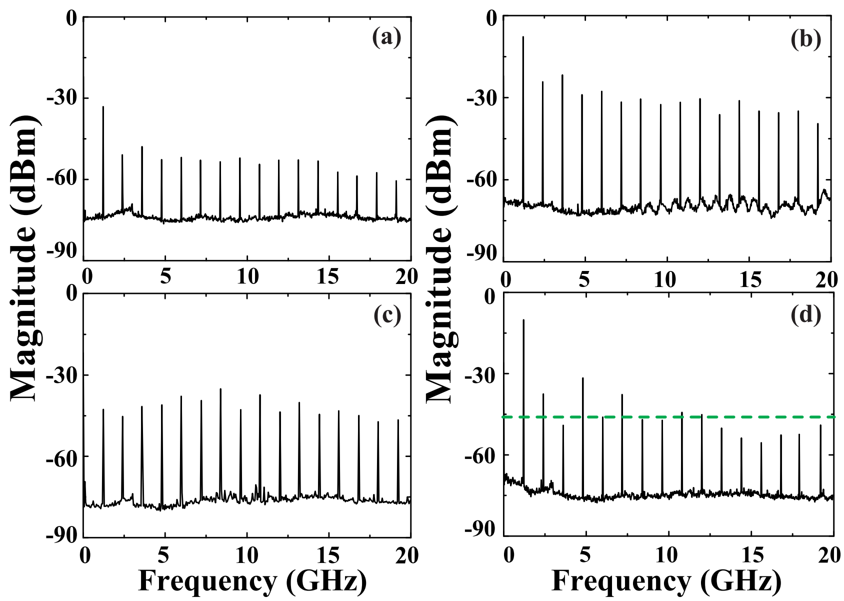


**Figure 2.** Power spectra of (a) the ML output generated by optoelectronic feedback and the SL output when subjected to (b) electric modulation, (c) optical injection, and (d) both electric modulation and optical injection from the ML output. Dashed line: average magnitude.

Figure 2(a) shows the power spectrum of the ML operating at the regular pulsing state under optoelectronic feedback with conditions of $f_{rep} = 1.2$ GHz, $J = 27.1$ mA, $\xi_f = 0.33$, and $t_d = 82$ cm. As can be seen, only the fundamental frequency at 1.2 GHz has a relatively larger magnitude while magnitudes of the high-order components are lower limited by the electronic bandwidth of the feedback loop. Under such limitation, selecting channels other than the main channel at the fundamental frequency with sufficient gain is difficult. Therefore, to demonstrate an arbitrary channel selection, the repetitive pulse train from the ML is used to phase-locked the SL both optically and electrically.

Figure 2(b) shows the power spectrum of the SL subject to only the electric modulation from the ML output. The envelope of the spectrum distribution is similar to the regular pulsing state from the ML output, that only the fundamental frequency has a higher magnitude relative to the other high-order harmonics. Note that, the spurious noise seen on the noise floor corresponding to the feedback delay frequency of about 350 MHz is significantly enhanced by the SL around the relaxation frequency (the frequency of semiconductor laser tends to oscillate in free-running status) as shown in Fig. 2(b). Figure 2(c) shows the power spectrum of the SL subject to only the optical pulse injection from the ML with $J = 30.61$ mA, $\xi_p = 0.24$, $f_{rep} = 1.2$ GHz, and $\Omega_p = 15.7$ GHz. A broadband microwave frequency comb with amplitude variation of $\pm 5$ dB in a 20 GHz range is generated which is benefited by bandwidth enhancement effect and stable frequency-locked phenomena through optical injection.[19,20]

Figure 2(d) shows the power spectrum of the SL under double phase-locked condition by applying both the electric modulation shown in Fig. 2(b) and the optical pulse injection shown in Fig. 2(c) simultaneously. Benefited by the double phase-locked loops with combining advantages of optical injection and electric modulation,[21,22] the selection of the main channel with less spurious noise and stably phase-locked spectral distribution is achieved. The main channel with large suppression ratio to the average of the undesired channels is selected through electric modulation and stable frequency-locked spectral distribution with less spurious noise is contributed by optical injection. The suppression ratio of 41.8 dB between the main and the undesired channels is obtained. The difference between the main and the largest undesired channel is 30.3 dB. The selection technique proposed here is also a good narrowband filter with gain. Compared to other selection schemes which work by photonic methods such as microwave photonic filters utilizing fiber Bragg gratings[8,23] and single-mode selection in Fabry-Perot semiconductor laser utilizing injection locking method[24] with the suppression of about 14, 18, and 30 dB to the stopband, the double phase-locked technique shows a significant improvement.

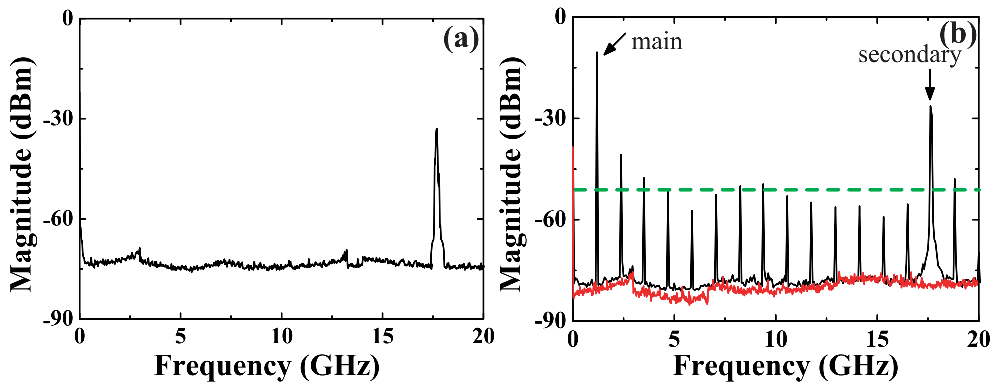


**Figure 3.** Power spectra of the SL output (a) under optical cw injection and (b) subject to both double phase-locked technique and optical cw injection. Dashed line: average magnitude. Red curve: background noise level.

In order to further select a secondary channel to communicate with the main channel, an optical cw injection is applied to the double phase-locked scheme. Under proper operational conditions, the SL is driven into a period-one (P1) state[25] through optical injection, which has the characteristics of continuously tuning frequencies and narrow spectral linewidths. The hybrid system composed of the double phase-locked loops and optical injection from a tunable laser (TL) shows the capability to demonstrate the arbitrary channel selection technique. Figure 3(a) shows the power spectrum of the SL under only optical cw injection with $\xi_t = 0.41$ and $\Omega_t = 17.3$ GHz. A period-one (P1) state with oscillation frequency of 18 GHz is observed as shown in Fig. 3(a). By further applying the P1 signal to the double phased-locked scheme as shown in Fig. 2(d), the power spectrum of the SL output with an enhanced amplitude at the $15^{th}$ channel is obtained as shown in Fig. 3(b). The average suppression ratios between the selected $1^{st}$ and $15^{th}$ channels to the undesired channels are about 44.5 and 25.9 dB, respectively. Differences of about 29.8 and 14.4 dB between the selected $1^{st}$ and $15^{th}$ channels to the largest undesired channel are observed, respectively. As the result, the secondary channel selection is realized in a semiconductor laser subject to both the double phase-lock and optical cw injection.

As shown in Fig. 4, the tunability of the selected secondary channel shows a linear relation to the optical injection strength. The linear relation between the selected frequency and the injection strength can be deduced from the characteristics of the P1 state generated by optical injection.[25] When applying the tunability behavior to the already double phase-locked system, the channel selection becomes tunable by properly adjusting the injection strength. Demonstration of selection range from 10.8 GHz to 18 GHz is achieved, which is limited by

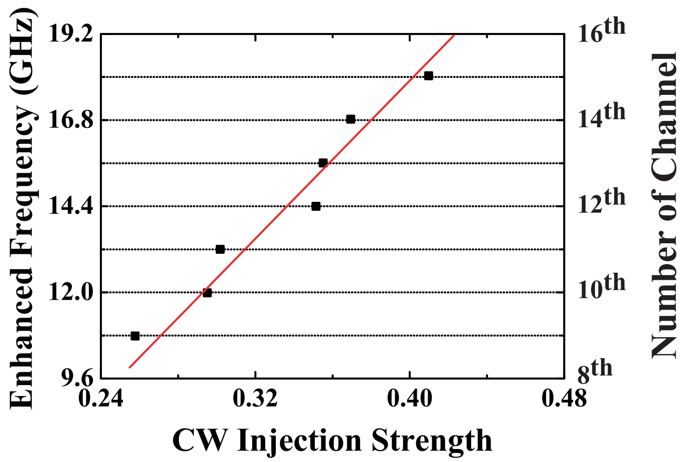


**Figure 4.** Linear tunability between cw injection strength and the selected frequency (channel).

the laser intrinsic relaxation oscillation and the 20 GHz bandwidths of the photodetector and power amplifier used. In this paper, the channel selection range of about 7.2 GHz is demonstrated.

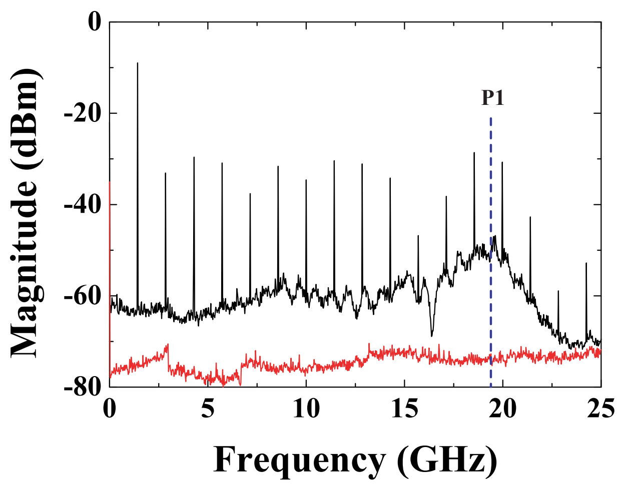


**Figure 5.** Power spectrum of SL chaotic output under combined double phase-locked loop and optical cw injection when $f_{rep} = 1.425$ GHz. Red curve: background noise level.

Note that, careful adjustment of optical cw injection strength is important in this system. The cw injection strength $\xi_t$ determines the oscillation frequency of the P1 state generated. If the generated oscillation frequency does not exactly match the frequency of the selected channel, the laser could be driven into chaotic oscillation state. Figure 5 shows the power spectrum with the same conditions as those used in Fig 2(d), except for the pulse repetition frequency $f_{rep} = 1.425$ GHz. In this case the harmonic pulsing frequency does not match the generated P1 frequency of 19.55 GHz. As can be seen, the SL becomes unstable and shows the clearly chaotic behavior as comparing to the background noise level (red line). Moreover, if the P1 frequency matches the harmonic frequencies exactly by carefully adjusting the injection strength, the stable phase-locked behavior as shown in Fig. 3(b) can be observed.

To examine the quality of the hybrid system for arbitrary channel selection, the single sideband (SSB) phase noise is measured to analyze the spectral purity. Figure 6 shows the SSB phase noise of the main ($1^{st}$) channel for the regular pulsing state of the ML (green) and for the SL outputs under single PLL (individually optical pulse injection (red) and electric modulation (cyan)) and double PLL (black), respectively. As can be seen, when

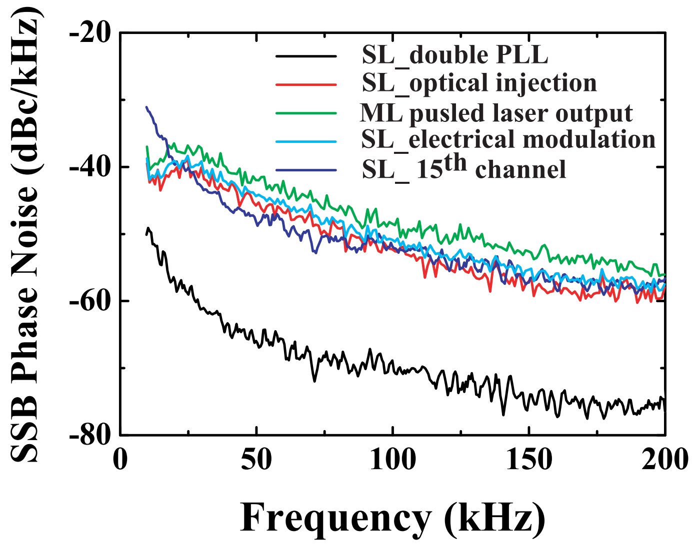


**Figure 6.** SSB phase noise of the $1^{st}$ channels of the pulsed laser output (green) and the SL output when applying optical injection (red), electric modulation (cyan), and double phase-lock loop (black), respectively. Blue curve is the SSB noise of the secondary ($15^{th}$) channel.

applying only the single PLL and double PLL, a SSB phase noise of −60 dBc/kHz (−90 dBc/Hz estimated) is achieved at offset frequencies of 200 and 25 kHz, respectively. A significant suppression of SSB noise is achieved when applying double phase-locked loops even without applying an external modulation by a commercial signal generator. The spectral purity generated by double phase-locked loops (SSB phase noise of about −105 dBc/Hz offset at 200 kHz) is comparable to the harmonic frequency-locked states of the negative optoelectronic feedback laser (SSB phase noise of about −83 dBc/Hz offset at 200 kHz)[26] and the optical frequency comb generated with the optoelectronic oscillator using phase modulator (SSB phase noise of about −95 dBc/Hz offset at 200 kHz).[27]

The SSB phase noise of the secondary ($15^{th}$) channel is also measured (blue). Note that, the SSB phase noise increases and accumulates as the order of the harmonics increases as expected. A SSB phase noise of the secondary ($15^{th}$) channel of −60 dBc/kHz is achieved at an offset frequency of 200 kHz, which is similar to the case as in the main ($1^{st}$) channel when the SL is under the single PLL. Clear suppression of the SSB phase noise in the whole frequency band (all channels) is observed when the SL is subjected to the double PLL. Therefore, the arbitrary channel selection system utilizing double phase-locked technique exhibits less SSB phase noise and spurious noise behavior, which can significantly reduce possibilities of the channel crosstalk and noise interference during the communication application.

To further exam the feasibility of the arbitrary channel selection system, the channel communication between the main and secondary channels is examined and analyzed. Figure 7 shows the power spectrum of the SL output with the selected main and secondary channels subject to both double phase-locked and optical injection (green line) as shown in Fig. 3(b). To demonstrate the channel talk between the selected main and secondary channels, an external microwave signal is modulated over the main channel.[28] Figure 7 shows the power spectrum after applying an sinusoidal signal at the $1^{st}$ (main) channel (black line). The sinusoidal signal is from the signal generator (Anritsu MG3690B) with a fixed output power of 0 dBm and frequency of 1.2 GHz which exactly matches the frequency of the selected main channel. As can be seen, through frequency mixing and energy redistribution, the applied signal is converted to all 16 microwave channels formed by the microwave frequency comb from 1.2 to 19.2 GHz. Furthermore, due to the stabilization resulted from applying an external modulation, the noise suppression deduced from the spectral linewidth narrowing of the secondary channel is obviously observed by comparing to the origin curve.

Moreover, by measuring the difference ratio (conversion gain) of the spectral peaks with and without the signal for each channel, the conversion gain of each channel for different signal power is obtained. The conversion

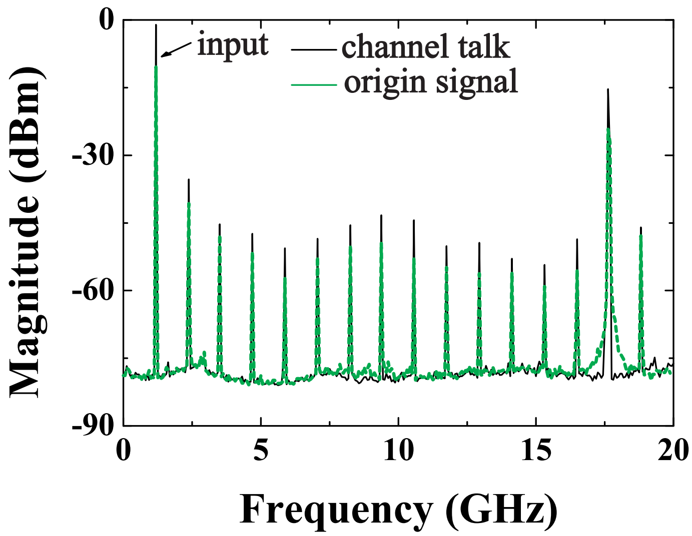


**Figure 7.** Power spectrum of the SL output subject to both double phase-locked technique and optical cw injection (green) and the spectrum after introducing a sinusoidal signal at the $1^{st}$ (main) channel (black).

gains of the main and secondary channels are about 11.38 and 11.02 dB, respectively. The averaged conversion gain of the undesired channels is about 4.9 dB. Due to the gain competition phenomena, the main and secondary channels with the relatively higher peak power gain more energy compared to the other undesired channels with lower peak power. The crosstalk between the selected main and secondary channels to the adjacent undesired channels are −29.8 and −21.54 dB, respectively. After applying an external modulation, the measured crosstalk between the selected and adjacent undesired channels are −34.27 and −30.6 dB for main and secondary channels, respectively. These results are better than those obtained with tunable ring resonators which have crosstalks of about −30 and −24 dB for the two selected channels.[9] Moreover, compared to the crosstalk of the origin signal, the channel talk ability is enhanced when applying additional message to the selected channels thanks to the gain competition behavior. Furthermore, the demonstration of channel talk when applying the external modulation at the $15^{th}$ (secondary) channel is also investigated. The conversion gain and spectrum distribution are similar to the case when modulating at the $1^{st}$ (main) channel.

## 4. CONCLUSIONS

In conclusion, we have demonstrated and characterized the arbitrary channel selection utilizing both the double phase-locked and optical injection schemes experimentally. The double phase-locked scheme is realized by both optical pulse injection and electric modulation to the slave laser from the master laser. Based on the microwave frequency comb generated by optical pulse injection, the 16 microwave channels formed by the comb lines with almost equally peak power are observed. By further applying an electric modulation to form the double phase-locked loops, the main channel is selected. Moreover, selection of a secondary channel is demonstrated by further applying an optical cw injection to the already double phase-locked slave laser. The selection range of about 7.2 GHz is achieved by adjusting the cw injection strength. Average channel suppression between the main and secondary channels to the undesired channels with ratios of 41.8 and 25.9 dB are obtained, respectively. The single sideband phase noise of −60 dBc/kHz is achieved at offset frequencies of 25 and 200 kHz for the desired main and secondary channels, respectively. Moreover, we also explore the feasibility of utilizing the generated arbitrary channel selection system in channel talk application. Spectral purity deduced from low single sideband phase noise and high conversion gain between the desired two channels exhibit good performance in reducing channel crosstalk and noise interference for channel communications. The crosstalk between the selected and adjacent undesired channels is less than −30.6 dB.

## ACKNOWLEDGMENTS

This work is supported by the National Science Council of Taiwan under contract NSC-97-2112-M-007-017-MY3.

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