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Narrow-linewidth single-frequency photonic microwave generation scheme by using an optically injected semiconductor laser with a filtered optical feedback has been proposed. The filtered feedback comes from a single feedback loop, which includes a narrow band-pass filter. With the filtered feedback, linewidth of the generated microwave can be significantly reduced from 22.4 MHz to 9.0 kHz with the side-peak suppression of 28 dB. The proposed scheme shows superior performance compared with the conventional single feedback configuration in terms of linewidth reduction and side-peak suppression. The proposed scheme also achieves better results compared with the complex dual feedback setting. The mechanism for the better performance of filtered optical feedback is that the filtered feedback can effectively limit the external cavity modes and stabilize the period one dynamics. In addition, the microwave linewidth decreases with the increase of the filter width until the optimized filter width is reached. Furthermore, the linewidth reduction and the side peaks suppression of photonic microwave using filtered optical feedback is relatively insensitive to the frequency detuning between the filter center frequency and the free-running frequency of the semiconductor laser.

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Microwave photonics technology has drawn considerable attention due to its wide applications in the fields of optical wireless communication, sensors and radar [1,2]. Microwave photonics technology can generally be classified into four categories: photonic generation, processing, control and distribution. Many techniques for the photonic microwave generation have been reported, which includes direct modulation, optical heterodyne, optical injection locking, external modulation, mode-locked semiconductor lasers, optoelectronic oscillator and period-one (P1) dynamics [3-15]. Among them, the P1 dynamics is one of the most promising photonic approaches. It has several advantages over the others, such as a nearly single sideband spectrum, which can enhance the power efficient, low cost due to the all-optical components configuration and a widely tunable frequency range from a few gigahertz to tens or even hundreds of gigahertz [8, 12-15]. P1 dynamics is one of many nonlinear dynamics in optically injected semiconductor lasers. P1 dynamics occurs when a stable locked laser experiences a Hopf-bifurcation [16], which induces two dominant frequencies: one is regenerated from the optical injection while the other one is the red-shifted cavity frequency. The phase noise induced by spontaneous emissions in semiconductor laser can greatly degrade the linewidth of P1 microwave [17-18]. Several techniques have been demonstrated to minimize the phase noise and reduce its linewidth, such as using double-locking with a microwave source [14], dual-beam optical injection [11], optoelectronic feedback [19], combining optical injection and polarization-rotated optical feedback [20] and optical feedback [17-18, 21]. Optical feedback is a simple and low-cost method to achieve linewidth reduction. However, with higher optical feedback strength, P1 dynamics is collapsed, which limits the linewidth reduction. Fischer et al. [22] reported that certain dynamics of the semiconductor lasers can be suppressed using narrow bandwidth filtered optical feedback. In this letter, we numerically investigate the property of the photonics microwave generated in an optically injected

semiconductor laser with a filtered optical feedback (FOF), which, to the best of our knowledge, has not been studied. The results demonstrate that very narrow-linewidth single-frequency of photonic microwave can be achieved in this configuration.

In the proposed configuration, a continuous-wave optical signal generated by a master laser (ML) is unidirectionally injected into a slave laser (SL) and a portion of the SL output is fed back through a feedback loop. The feedback loop contains an optical bandpass filter. For simplicity, the optical bandpass filter is simulated by a Lorentzian filter. Accordingly, the dynamics of the SL with optical injection and filtered feedback can be modeled by modified single-mode rate equations [22-25].

$$\frac{da}{dt} = \frac{1-ib}{2}[\frac{\gamma_c\gamma_n}{\gamma_s J}n - \gamma_p(|a|^2-1)]a + \xi\gamma_c e^{-i2\pi f_i t} + \eta\gamma_c F + \chi \quad \textbf{(1)}$$

$$\frac{dn}{dt} = -(\gamma_s + \gamma_n|a|^2)n - \gamma_s J(1-\frac{\gamma_p}{\gamma_c}|a|^2)(|a|^2-1) \quad \textbf{(2)}$$

$$\frac{dF}{dt} = \Lambda a(t-\tau)e^{-i\omega\tau} + (i\upsilon-\Lambda)F \quad \textbf{(3)}$$

where, a and n denote the normalized field amplitude and carrier density, respectively. F denotes the field amplitude of the FOF light. γ_c is the cavity decay rate, γ_s is the spontaneous carrier relaxation rate, γ_n is the differential carrier relaxation rate, γ_p is the nonlinear carrier relaxation rate, b is the linewidth enhancement factor, and J is the normalized bias current. f_i and $\upsilon=\omega_f/(2\pi)$ are the offset frequency of optical injection and the center frequency of filter with respect to the free-running frequency $f_0 = \omega_f/(2\pi)$ of the SL, respectively, and Λ is the half-width at half-maximum (HWHM) of Lorentzian filter, ξ represents the optical injection strength, η is the feedback strength, and τ is the feedback round-trip time. The spontaneous emission noise is modeled by a Langevin fluctuating force χ, of which the real and imaginary parts are mutually independent. R_{sp} is used to describe the strength of χ [26]. The typical parameters values used in the reference [18] are adopted in this simulation, where $\gamma_c = 5.36 \times 10^{11}$ s^{-1}, $\gamma_s = 5.96 \times 10^{9}$ s^{-1}, $\gamma_n = 7.53 \times 10^{9}$ s^{-1}, $\gamma_p = 1.91 \times 10^{10}$ s^{-1}, b=3.2, J=1.222, f_0 = 193.41 THz. With these parameters, the relaxation oscillation frequency of the free-running laser is 10.25 GHz. R_{sp} is set at 5.99×10^{19} V^{2}m^{-1}s^{-1} to approach the linewidth of the generated microwave observed in the experiment [17]. In this letter, we emphasize the feedback effect on the linewidth reduction of the generated microwave, the injection parameters (f_i, ξ) are fixed at (15 GHz, 0.17) unless stated otherwise. With these injection parameters, the SL operates at P1 dynamics.

A second-order Runge-Kutta integration method is used to numerically solve Eqs. (1-3) with a time step of 1 ps. The optical spectrum and radio frequency (RF) spectrum are calculated by adopting FFT to the field amplitude and intensity, respectively. The linewidth is calculated from the smooth RF spectra using MATLAB's default moving averaging. A time span of 1 ms is adopted for the microwave linewidth analysis, while a time duration of 5 μs is used for the rest of other analyses.

Figure 1 shows the optical spectra (left column) and radio frequency (RF) spectra (right column) of the SL. Figs. 1(a1) and (a2) are the optical spectrum and RF spectrum of the optically injected SL without optical feedback. From the perspective of optical spectrum, as shown in Fig. 1(a1), the optical injection is regenerated in the SL and many oscillation sidebands are also emerged due to the P1 dynamics [18]. With these injection parameters, the red-shifted cavity frequency of SL without feedback is about -9.06 GHz. Therefore, the frequency of the generated microwave is 24.06 GHz, as shown in Fig. 1(a2). We add an optical feedback loop that includes a bandpass filter to the setup. The center frequency of filter υ is set near the red-shifted cavity frequency at -9 GHz, so that the output around the red-shifted cavity frequency of the SL can be fed back to the SL. The HWHM of filter is fixed at Λ=160 MHz and the feedback parameters (η, τ) are chosen to be (0.025, 2.4 ns). The resulted optical spectrum and RF spectrum are plotted in Figs. 1(b1) and (b2), respectively. The result in Fig. 1(b2) shows that the microwave linewidth has reduced from the 22.4 MHz without the optical feedback to 9 kHz. In Fig. 1(b2), we also observe some side peaks (SPs) with the separation determined by the delay time, which is similar to the result with single optical feedback [17-18], but the amplitudes of the side peaks are much smaller. To quantify the SP in RF spectrum, the side-peak suppression coefficient (SPSC) is introduced and is defined as the ratio of the power of fundamental microwave frequency to the maximum SP. In Fig. 1(b2) with FOF, the SPSC reaches 28.5 dB. In this case, the generated microwave can be considered as a single frequency microwave. In order to illustrate the outstanding performance of FOF in reducing the microwave linewidth and suppressing the SPs, the spectra of the SL with conventional single optical feedback (SOF) and double optical feedback (DOF) are also simulated. For the conventional optical feedback, equation (3) does not need to be included, the feedback term F in equation (1) is written as $a(t-\tau)e^{i\omega\tau}$ and $(a(t-\tau_1)e^{i\omega\tau_1} + a(t-\tau_2)e^{i\omega\tau_2})/2$ for SOF and DOF, respectively. τ_1 and τ_2 are the feedback round time from cavity 1 and 2, respectively. From the feedback term, we can see that the equal feedback power from both external cavities for DOF are considered. Fig. 1 (c1) and (c2) present the optical and RF spectra of the SL subject to optical injection and SOF with the same feedback parameters used in Fig.1 (b). Fig. 1(c2) shows that SOF can also significantly reduce the microwave linewidth from 22.4 MHz without optical feedback to 15.8 kHz, but many more SPs are excited, which is in line with the reported results [17-18], and the SPSC decreases to 14.7 dB. Given the external-cavity producing many side peaks (representation of external-cavity modes (ECMs)) around the red-shifted frequency in the optical spectrum [inset in Fig. 1(c1)], SPs in the RF spectrum can be attributed to the direct induction by the ECMs. The excitation of the strong SPs in the RF spectrum can greatly compromise the quality of the microwave. In order to suppress the side peaks in the RF spectrum, the complex double feedback has been proposed and demonstrated [17-18]. Figs. 1 (d1) and (d2) present the optical spectrum and RF spectrum of the SL subject to DOF, respectively. The total feedback strength is the same as that used in Figs. 1(c1) and (c2) and τ_1 =2.4 ns, τ_2 =3 ns. Fig. 1(d1) shows that the side peaks around the red-shifted cavity frequency under the DOF have been significantly suppressed due to the competition of ECMs induced by two feedbacks with different round-trips times. As a consequence, the SPs in the RF spectrum are suppressed with a SPSC of 23.8

dB. The microwave linewidth also reduces slightly to ~14.4 kHz compared with that for SOF. The above results have clearly demonstrated that the performance of the FOF is superior to the conventional SOF and DOF. The linewidth is about 1.7 and 1.6 times narrower than those with SOF and DOF, respectively. The SP suppression in FOF is 13.8 dB better than the SOF and 4.7 dB better than the DOF. The great performance of FOF can be attributed to the suppression of ECMs, as shown in the inset of Fig. 1(b1).

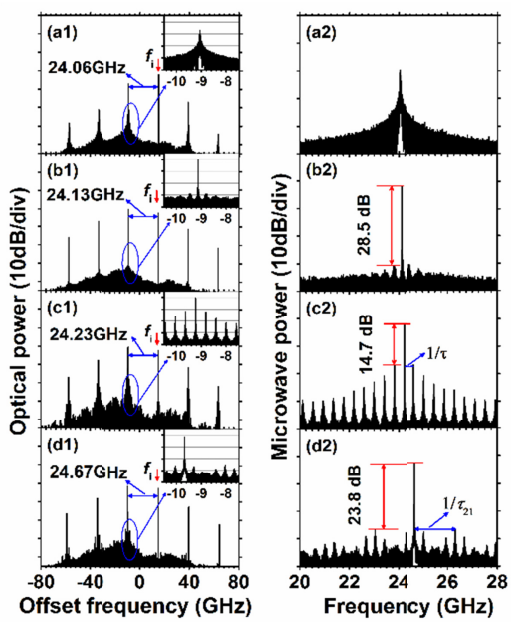

Fig. 1. Optical spectra (left column) and RF spectra (right column) of the SL subject to optical injection and (a) without optical feedback, (b) with FOF, (c) with SOF and (d) with DOF.

The influence of feedback strength on the P1 dynamics are also inspected. Fig. 2(a) and (b) present the microwave linewidth and the SPSC as a function of the feedback strength, respectively. The injection parameters, feedback delay times and the filter parameters are the same as those used in Fig. 1. The results in Fig. 2(a) demonstrate that the linewidth reduction in both the SOF and FOF hold evident advantages over the DOF configuration for the weak feedback. With the increase of the feedback strength, the linewidths of the generated microwave decrease for all the three cases of optical feedback, however, the reduction speed for DOF is much faster than both cases of SOF and FOF until the feedback strength reaches 0.01. For the feedback strength between 0.01 and 0.03, the linewidth reduction become comparable for all three types of feedback. For SOF and DOF, the linewidth gradually reaches their optimal value at about 10 kHz with the feedback strength of 0.03. Further increase of the feedback strength, the microwave linewidth increases again. This is because the dynamics of the SL starts to be driven out of P1 dynamics and enter into complex dynamics, such as period-double, quasi-periodicity and chaos. For the proposed FOF configuration, the linewidth reduction is continuous for higher feedback strength since the filter has attenuated ECMs of the feedback beam. The results clearly indicate that the FOF configuration can achieve narrower linewidth compared with the conventional optical feedback. The SPSC as a function of the feedback strength is shown in Fig. 2(b). For SOF configuration, the SPSC shows monotonous decreasing trend, whereas for DOF configuration, the SPSC increase with the increasing feedback strength for the weak feedback strength. Then the suppression coefficient remains a relative high value until the optimized feedback strength of about 0.032, as shown in Fig 2(a). Further increase the feedback strength, the SPSC exhibits oscillation drop. This oscillation is due to the red-shifted cavity frequency shifts toward other ECMs with the increasing of feedback strength. For the FOF configuration, it presents much better SPSC compared with SOF and DOF. The change of the SPSC shows an evident increasing trend with the increase of feedback strength.

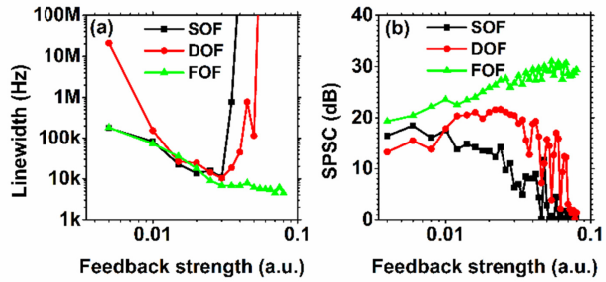

Fig. 2. (a) Linewidth and (b) SPSC as a function of feedback strength. The injection parameters (f_i, ξ) = (15GHz, 0.17).

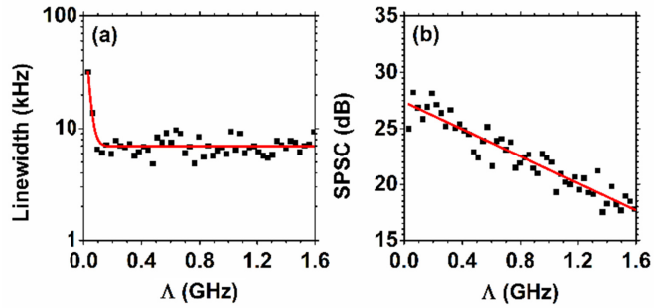

Fig. 3. (a) Linewidth and (b) SPSC as a function of filter HWHM. η=0.035, τ= 2.4 ns, υ=-9 GHz. The red lines are fitting curves.

The performance of FOF is affected by the filter HWHM. Fig. 3 presents the microwave linewidth and the SPSC of the generated microwave as a function of the filter HWHM. The injection parameters and feedback delay time are the same as those used in Fig.2 and the injection strength is set at 0.035. The red lines in Fig.3 are the fitting curves. The fluctuations in the figure is believed to be due to the nature of noise. In the simulation, large noise is used to simulate the wide linewidth of the SL without optical feedback. The results in Fig. 3(a) indicate that when the filter HWHM is less than 0.1 GHz, the generated microwave linewidth decreases with the increasing filter HWHM. Further increase the filter HWHM, the

microwave linewidth tends to a relative stable value with small fluctuations, and slightly increasing trend. This is because the feedback power is related with the filter HWHM. The feedback power grows rapidly with the enlarging filter HWHM for the small HWHM of the filter. When the filter HWHM increases to certain value where most of the power has passed the filter, the feedback power will increase little with further increase of the filter HWHM. In the simulation, we find that when the filter HWHM increases to 50 GHz, the result is similar to conventional SOF. Fig. 3(b) plots the SPSC as a function of the filter HWHM. The result demonstrates that the SPSC almost exponentially decreases with the increasing filter HWHM. This can be attributed to the increase of the ECMs with increase of the filter HWHM, thus destabilize the P1 dynamics and degrade the performance of the SP suppression.

The frequency detuning between the filter center frequency and the free-running frequency of the SL also plays a significant role in the filtered feedback. Figure 4 presents the influence of the frequency detuning on the P1 microwave. As it is shown, the linewidth reduction can be retained in a large detuning range from -10.2 GHz to -8GHz. Similarly, the SPSC can also hold a relatively large value at these frequency detuning range. The fluctuation in the SPSC is due to the variation of ECMs under profile of optical filter. When the detuning frequency is out of this range, the linewidth of the microwave presents a fast increasing and finally stable itself at about 1MHz, which is comparable to the SOF case.

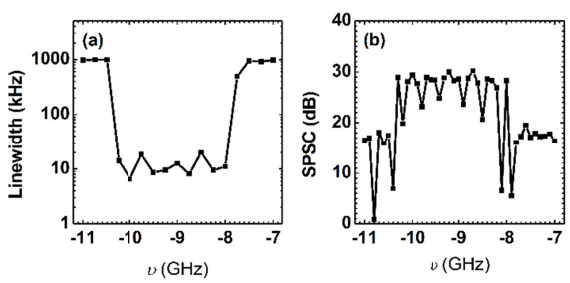

Fig. 4. (a) Linewidth and (b) SPSC as a function of the frequency detuning. η=0.035. τ= 2.4 ns, and Λ=160 MHz.

In conclusion, we have numerically investigated effect of filtered optical feedback on the linewidth reduction and side peaks suppression of the generated photonic microwave based on P1 dynamics of an optically injected semiconductor laser. The results demonstrate that the proposed FOF configuration presents significant advantages over the conventional optical feedback in terms of linewidth reduction and side peaks suppression. The microwave linewidth decreases with the increasing feedback strength. The laser is very robust to FOF and remains in P1 dynamics even with a very high feedback strength, therefore very narrow microwave linewidth can be achieved with FOF. The mechanism for the better performance of FOF compared with the conventional feedback is that the filtered feedback can effectively limit the ECMs and stabilize the P1 dynamics. The simulation results also show that the microwave linewidth decreases with the increasing filter HWHM for the lower filter HWHM. This is because the total feedback power increases with the increase of the filter HWHM. Further increase the filter HWHM has little effect on the linewidth reduction. On the other band, the side peaks suppression coefficient decreases with the increase of the filter HWHM. Therefore, the HWHM of the filter should be carefully selected for this application. In addition, the linewidth reduction and the side peaks suppression of photonic microwave using FOF are quite tolerant to the frequency detuning between the filter center frequency and the free-running frequency of the optically injected semiconductor laser. The linewidth reduction and higher side-peaks suppression can be retained at the frequency detuning range of 2GHz.

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