

Analysis of performance of RFS-based optical comb influenced by linewidth of laser source

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The laser source is an important element whose properties have influence on the output performance of single sideband (SSB) optical comb based on recirculating frequency shifter (RFS). The theoretical and experimental results show that the tone-to-noise ratio (TNR), flatness, and stability of optical comb improve using laser source with narrower linewidth. In order to obtain the optical comb with TNR larger than 42 dB and degree of stability (DOS) smaller than -6.7 dB, external cavity laser (ECL) with linewidth from 100 kHz to 1 MHz is a trade-off choice.

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Optical comb with flat spectrum and high tone-to-noise ratio (TNR) has many applications such as reconfigurable optical pulse generator^[1], microwave signal generation^[2], and optical signal processing^[3]. In particular, coherent dense wavelength division multiplexing (Co-DWDM) or optical orthogonal frequency division multiplexing (OOFDM) based on optical comb is considered as a critical technology for the Tb/s per-channel optical communication^[4–6]. There are several methods to generate optical comb, such as super-continuum technique based on fiber nonlinear effects^[7], placing cascaded phase modulators (PMs) into an erbium-doped optical fiber amplifier (EDFA) loop^[8], and single sideband (SSB) modulator with recirculating frequency shifter (RFS)^[9–11]. Among the three technologies mentions above, the last one has the notable advantages of low driving voltages, flexible control, and accurate frequency spacing.

The performance analysis of optical comb generation based on RFS has been discussed, including the effects of polarization controller^[12], I/Q modulator (IQM)^[10], EDFA^[13], and harmonics^[14,15]. After further research, we find that the linewidth of the laser source can also influence the optical comb performance.

In this letter, we theoretically analyze the influence of laser linewidth on the optical comb generation. The broaden of laser linewidth will result in a degradation on TNR of output spectrum. The flatness and the stability of carrier's output power will also deteriorate. Numerical simulations on the output spectra of optical comb generation system with different laser linewidths are conducted. Experimental results are in good agreement with the theoretical results and simulations. In addition, the simulation results about the 45th subcarrier with different laser linewidths indicate the performance of optical comb

becomes gradually steady when the laser linewidth decreases to a certain degree.

Figure 1 shows the schematic diagram of the optical comb generator based on RFS, which consists of a laser source, a 50:50 coupler, an IQM for frequency shift, an optical band-pass filter (OBPF) with appropriate bandwidth to control the subcarriers number, an optical amplifier (OA) to compensate the loop loss and two polarization controllers (PCs) used to control the stabilization of the polarization states. In order to determine the influence of laser linewidth, two kinds of typical laser source, the distributed feedback (DFB) lasers with linewidth of 8 MHz and external cavity lasers (ECLs) with linewidth of 100 kHz, have been acted as continuous wave (CW) light source respectively.

Assume the optical signal from the CW laser obeys Lorentzian line shape^[16]:

$$P(f) = \frac{A^2}{\pi\Delta\nu} \cdot \frac{1}{1 + [(f-f_0)/\Delta\nu]^2}, \quad (1)$$

where f_0 is the central frequency, $\Delta\nu$ represents the linewidth of the laser, $\frac{A^2}{2}$ is the output power of laser, and T denotes the transfer function of IQM which neglects the 5th order crosstalk^[11]

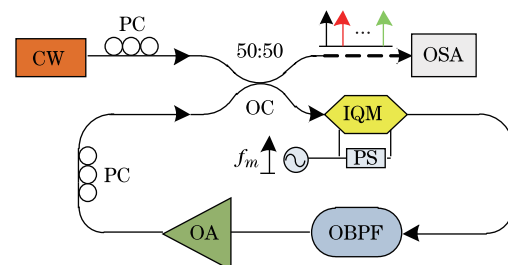


Fig. 1. Schematic of optical comb generation based on RFS. PS: phase shifter; OC: optical coupler.

$$T = \exp(j2\pi f_m t) + b_3 \exp(-j6\pi f_m t), \quad (2)$$

where $b_3 = -J_3(\delta_m)/J_1(\delta_m)$ stands for the 3rd order crosstalk coefficient, here $\delta_m = (\pi V_{pp})/2V_\pi$ denotes the phase modulation depth, V_{pp} is the amplitude of radio frequency (RF) signal, V_π stands for the half-wave voltage of the Mach-Zehnder modulator (MZM) in each branch of IQM, and f_m is the frequency shift. In order to confirm the influence of laser linewidth on the spectrum of optical comb, we will conduct the analysis in frequency domain. Through Fourier transformation (FT), the transfer function of IQM is

$$\text{FT} = \delta(f - f_m) + b_3 \delta(f + 3f_m). \quad (3)$$

So after one round trip the output spectrum in frequency field can be expressed as

$$F1 = P(f) * \text{FT} = \frac{A^2}{\pi \Delta v} \cdot \frac{1}{1 + \left[\frac{2(f - (f_0 + f_m))}{\Delta v} \right]^2} + b_3 \cdot \frac{A^2}{\pi \Delta v} \cdot \frac{1}{1 + \left\{ \frac{2[f - (f_0 - 3f_m)]}{\Delta v} \right\}^2}. \quad (4)$$

It is obvious that the linewidth of first tone is still Δv according to Eq. (4). In the same way, we can conclude the linewidth of each tone will also be Δv .

The sketch about the influence of laser linewidth on TNR of optical comb is shown in Fig. 2. In the premise of equal output power, the laser peak power can be expressed as

$$P_{\max} = \frac{A^2}{\pi \Delta v}. \quad (5)$$

According to Eq. (5), we can conclude that the laser peak power is inversely proportional to the linewidth. For example, the laser peak power decreases 19 dB when the linewidth of the laser is 8 MHz, compared with 100 kHz. In actual experiment, due to the resolution of the optical spectrum analyzer (OSA), the difference may be not so obvious.

Furthermore, take the first two tones as example, the intersection point is $f_0 + 1.5f_m$ based on the conclusion that the linewidth of each tone is Δv and the power at this point is

$$g = \frac{2A^2}{\pi \Delta v} \cdot \frac{1}{1 + \left(\frac{f_m}{\Delta v} \right)^2} \approx \frac{2A^2}{\pi f_m^2} \cdot \Delta v. \quad (6)$$

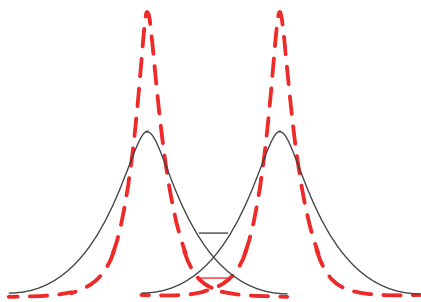


Fig. 2. Sketch about influence of laser linewidth on TNR of optical comb.

Here, we define the power below intersection point as “unwanted” noise due to they will interference each other and it is proportional to the laser linewidth according to Eq. (6). For example, the noise power for linewidth of 8 MHz is 19 dB higher than that for 100 kHz. However, considering amplified spontaneous emission (ASE) noise accumulation due to OA, the influence of linewidth on noise power will be partially buried in ASE noise and the noise difference between the cases for two linewidths will be degraded.

The laser linewidth not only influences the TNR of optical comb, but also on the flatness and stability of comb. Suppose the 5th order crosstalk is neglected, the outputs after N -round trips are

$$E_{\text{out}} = E_{\text{in}}(t) \cdot \sum_{n=0}^N T^n = E_0 e^{j[\omega t + \phi(t)]} \cdot \sum_{n=0}^N T^n \approx E_0 e^{j\omega t} \cdot \sum_{n=0}^N \{ \exp(j2\pi n f_m t) + n b \exp[j2\pi(n-4) f_m t] \} \cdot e^{j\phi(t)}, \quad (7)$$

where $\phi(t)$ is a random variable due to the laser linewidth and it will induce crosstalk $n b \exp[j2\pi(n-4) f_m t]$ superimposed on arbitrary optical subcarrier. The amplitude and output power of n th tone will be

$$E_n = E_0 e^{j(\omega_0 t + \phi_1)} \cdot e^{j2\pi n f_m t} + k b \cdot E_0 e^{j(\omega_0 t + \phi_2)} \cdot e^{j2\pi n f_m t} = E_0 \sqrt{1 + (k b)^2 + 2k b \cdot \cos(\varphi_1 - \varphi_2)} \cdot e^{j2\pi n f_m t}, \quad (8)$$

$$P_n = E_0^2 \cdot [1 + (k b)^2 + 2k b \cos(\varphi_1 - \varphi_2)], \quad (9)$$

where ϕ_1, ϕ_2 are values of $\phi(t)$ which changes with time, the first term presents wanted tone generated by the n th round trip, the second term presents 3rd harmonic component generated by the k th round trip. Constructive interference between the two terms occurs at some tones frequency points but destructive interference at other frequency points which leads to deterioration in flatness of optical comb.

Within a time interval τ , $\varphi_1 - \varphi_2 \sim N(0, 2\pi \Delta v |\tau|)$ ^[16] Assuming $\tau = 5 \times 10^{-8}$ s, the variance of $\cos(\varphi_1 - \varphi_2)$ with laser linewidths of 100 kHz and 8 MHz are 0.0005 and 3.155. It is obvious that the narrower the laser linewidth, the more stability the optical comb will be.

Simulations are carried out based on the setup shown in Fig. 1. The resolution of OSA used in all simulations is 20 MHz including the calculation. The linewidths of laser sources are 100 kHz and 8 MHz respectively, the power of the CW laser is 11.5 dBm, and the carrier frequency interval is $f_m = 10.7$ GHz. The bandwidth of the filter covers the range from $f_0 + f_m$ to $f_0 + 45f_m$, which can generate 45 valid carriers getting through it. The saturated output power of the EDFA is 25 dBm. From the simulations, we can obtain the following conclusions.

Firstly, optical comb of 45 tones with the laser linewidths of 8 MHz and 100 kHz are obtained by the simulation as shown in Fig. 3. It is obvious that the output spectrum with laser linewidth of 100 kHz generates higher average peak power and lower noise power. Then we can conclude that the narrower the laser linewidth, the higher TNR the output spectrum will be.

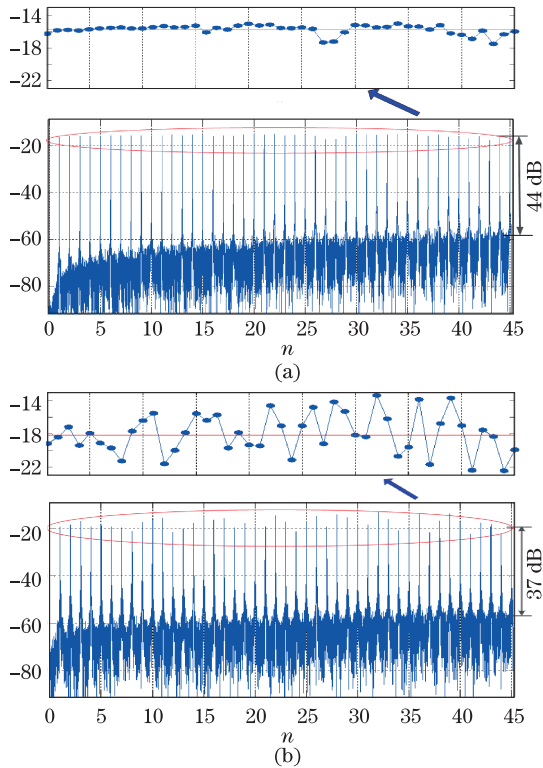


Fig. 3. Simulation results of 45 tones and detail variation about peak power with the laser linewidths of (a) 100 kHz and (b) 8 MHz.

Secondly, we adopt the quantity error vector magnitude (EVM)^[17] to express the degree of flatness of the output spectrum, which is defined as

$$\text{EVM}_{\text{RMS}} = \sqrt{\frac{\frac{1}{N} \sum_{i=1}^N |P_i - P_{\text{avg}}|}{P_{\text{avg}}}} \cdot 100\%, \quad (10)$$

where P_i is the power of the i th subcarrier, and P_{avg} is the average peak power of the output subcarriers. The detail variation about peak power with linewidths of 8 MHz and 100 kHz are also shown in Fig. 3 and the EVM with laser linewidths of 100 kHz and 8 MHz are 29.31% and 38.08% respectively. Obviously, the output spectrum gets flatter as the linewidth of laser source becomes narrow.

Thirdly, the spectral envelopes of 45 tones with linewidths of 8 MHz and 100 kHz after different recirculation loops are displayed in Fig. 4. Figures 4(a) and (b) are the optical comb outputs with laser linewidths of 100 kHz and 8 MHz respectively. The solid line and dash line correspond to circulate 130 times, 160 times in each part. Here, we use different circular times to characterize different time in order to examine the change of spectral envelopes, namely stability. 130 times and 160 times are chosen in the simulation which are more than 49 times^[14], that is because the filter in the loop is super-Gaussian shape rather than ideal rectangular in order to approximate the experimental conditions. Obviously, the fluctuation of spectra peak power over time varies with laser linewidth. At the same time, we also define degree of stability (DOS) to quantify the output

spectrum, which is shown as

$$\text{DOS} = 10 \lg \left(\frac{\sum_{i=1}^N |P_{1,i} - P_{2,i}|}{N \cdot P_{\text{avg}}} \right), \quad (11)$$

where $P_{1,i}$ is the peak power of the i th subcarrier after circulated 130 times, $P_{2,i}$ is the peak power of the i th subcarrier after circulated 160 times, and P_{avg} is the average peak power of the output subcarriers. The relationship between the laser linewidth and DOS is displayed in Fig. 5. It can be concluded that the narrowing of laser linewidth could improve the stability of output spectrum.

To further study the influence of laser linewidth on the optical comb output, the experimental setup is implemented as shown in Fig. 1. As the output spectrum is unstable, we grasp one figure for laser linewidths of 8 MHz and 100 kHz respectively. The power and the wavelength of the optical source are 11.5 dBm and 1559.59 nm, the frequency of the RF signal is 10.7 GHz. In

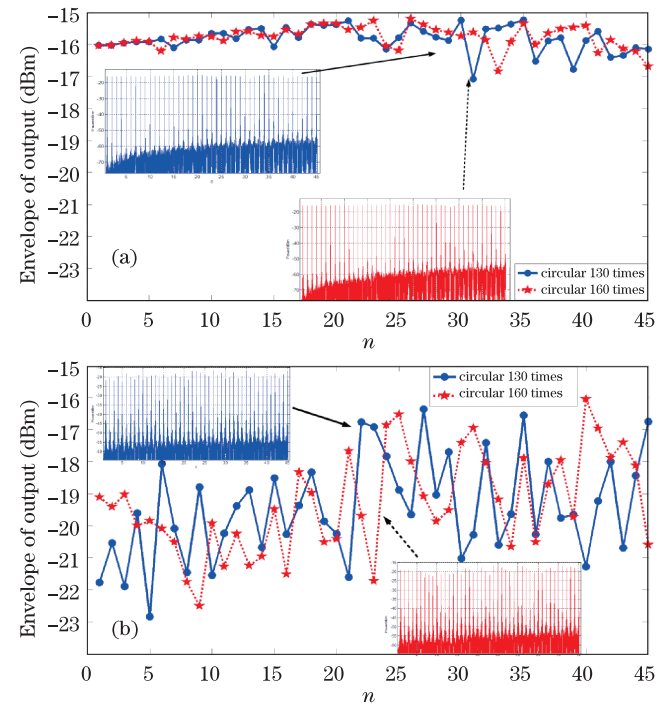


Fig. 4. Spectral envelope of 45 tones after different recirculation loops with laser linewidths of (a) 100 kHz and (b) 8 MHz.

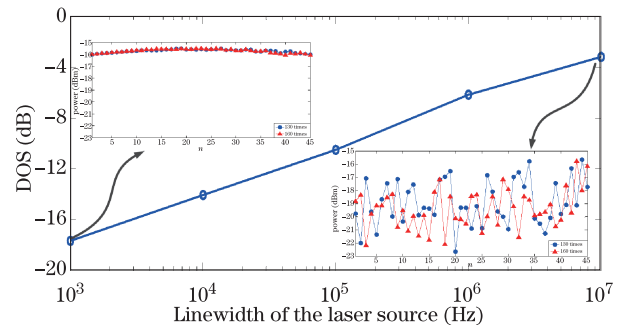


Fig. 5. DOS of optical comb with different laser linewidths.

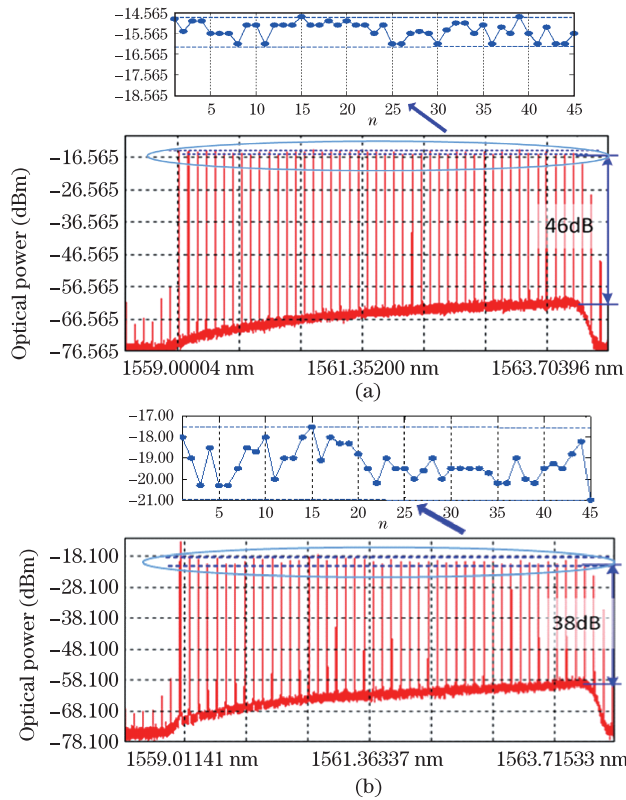


Fig. 6. Experimental results of 45 tones with the laser linewidths of (a) 100 kHz and (b) 8 MHz.

addition, the saturated output power of EDFA is set 25 dBm, the insertion losses of IQM, filter, and OC are about 13, 5, and 3 dB, respectively, and the resolution of OSA is 20 MHz. The experimental results of 45 tones with the laser linewidths of 8 MHz and 100 kHz are shown in Fig. 6.

Experimental results about average peak power and EVM generated by the laser linewidths of 8 MHz and 100 kHz are listed in Table 1. From the Table 1, we can conclude that average peak power with linewidth of 100 kHz shows about 3-dB improvement compared with that of the 8 MHz. The distinction between theoretical analysis results and experimental results comes from the resolution of OSA, which displays

$$\int_{-10 \text{ MHz}}^{10 \text{ MHz}} \frac{A^2}{\pi \Delta v} \cdot \frac{1}{1+(2f/\Delta v)^2} df =$$

$$\frac{A^2}{2\pi} \cdot \arctan(2f/\Delta v) \Big|_{-10 \text{ MHz}}^{10 \text{ MHz}}$$

difference of the peak power. The experimental results about n th tone noise power when using the lasers with linewidth of 100 kHz and 8 MHz are listed in Table 2, which show that the narrower the linewidth of the laser source, the lower the noise power of optical comb. It is indicated that using narrower laser linewidth could improve the TNR of optical comb. The experimental results are in good accordance with the theoretical and numerical analysis.

Table 1 also confirms that the narrower the linewidth of the laser source, the more flatten the generated optical comb will be. Further, we also can see from Table 2 that the noise power difference between different linewidths of laser sources decreases with the increased number of cycle index. This is exactly caused by the effect of ASE accumulation as mentioned above. Generally, ASE noise

has more influences on the noise floor of optical comb, but for the first several tones or when the laser linewidth increases to a certain degree, the influence of noise due to laser linewidth is also very significant.

In order to be the guide how we make a good choice of lasers with appropriate linewidth in generation of optical comb, we also simulate the TNR of the 45th tone with different laser linewidths, as shown in Fig. 7. From the theoretical analysis and simulations above, we can conclude that the narrower the laser linewidth, the higher the tone-to-noise will be, which is consistent with the general trend of Fig. 7. Furthermore, we can see that the TNR of the 45th tone will become gradually stable, when the linewidth of laser source decreases to a certain extent in Fig. 7. It is because the ASE noise plays an important role in this situation. Furthermore, the resolution of OSA will limit to identify the TNR difference when the linewidth is narrower than 100 kHz. In order to obtain the optical comb with $\text{TNR} > 42$ dB and $\text{DOS} < -6.7$ dB, considering the cost and the performance improvement, ECL with linewidth from 100 kHz to 1 MHz is a trade-off choice (in this range, the narrower the better).

In conclusion, we theoretically analyze the influence of the laser linewidth on the performance of optical comb generation. The broaden of laser linewidth leads to a degradation to TNR of output spectrum, and the flatness and stability of carrier's output power also deteriorate. Numerical simulations on the output spectra of optical comb generation system with different laser linewidths are conducted. Experimental results are in good agreement with the theoretical results and simulation. In addition, the simulation results about the 45th subcarrier with different laser linewidths indicate the performance of optical comb becomes gradually steady when the laser linewidth decreases to a certain degree.

Table 1. Average Peak Power and EVM with the Laser Line Width of 100 kHz and 8 MHz

	Average Peak Power (dbm)	EVM
100 kHz	-16.06	28.34%
8 MHz	-19.41	37.20%

Table 2. n th Tone Noise Power (dBm) with the Laser Linewidth of 100 kHz and 8 MHz

	1st Tone	15th Tone	30th Tone	45th Tone
100 kHz	-74.065	-66.565	-63.565	-61.065
8 MHz	-70.050	-63.100	-60.600	-58.600
Difference	4.015	3.465	2.965	2.465

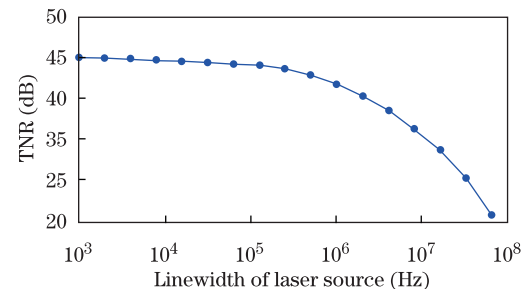


Fig. 7. TNR of 45th tone with different laser linewidths.

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