Study on Spectral Linewidth Characteristics of Parametric Optical Frequency Comb

Ting CAO, Juanjuan YAN, Aihu LIANG, Jing CHEN

ABSTRACT

This paper describes the frequency comb generation in a parametric mixer based on a section of highly nonlinear fiber (HNLF), and spectral linewidth characteristics of the generated parametric comb lines are investigated for the first time. In the experiments, the parametric mixer is driven by electro-optical modulated continuous-wave, and combs with about 40 lines are obtained. The linewidth of the tones with different orders is measured. The results show that the parametric comb lines are characterized with spectral linewidth preservation.

INTRODUCTION

Optical frequency comb (OFC) has been regarded as one of the most important optical innovations of our time due to their applications in high-precision metrology, sensing, spectral analysis, high energy radiation generation and so on.\(^1\) Optical frequency combs with a high degree of coherence, excellent spectral flatness, a broad bandwidth at high repetition rates, as well as stability are desirable for various applications such as wavelength division multiplexing, optical orthogonal frequency division multiplexing, and optical arbitrary waveform generation.\(^2\)

OFCs have long been generated by using a mode-locked laser.\(^3\) However, special methods are required to stabilize the operation. In recent years, a number of alternative approaches have been proposed for the generation of OFCs.\(^4\) Among these schemes, the method based on electro-optical modulation of a continuous-wave (CW) laser has been widely investigated due to its advantages of simplicity, stability and tunability.\(^5\) Cascaded intensity and phase modulators driven by external microwave sources are usually employed in this scheme. It has been found that the number of comb lines is determined by the modulation index of the phase modulator.\(^6\) However it is difficult to increase the RF power due to the limitation of the amplifier saturation output power. A frequency comb synthesis can also be
accomplished with the technique of parametric process.\textsuperscript{10-11} With this method, OFCs with more than 120 tones in a 100 nm-wide continuous band have been generated.\textsuperscript{12} When the pumps for the parametric process are phase-correlated by injection locking, the spectral linewidth broadening inherent to parametric comb generation can be cancelled.\textsuperscript{13} Two distributed feedback (DFB) slave lasers are required to achieve injection locking. So this kind of OFC generator is complex. In this paper, we investigate the linewidth characteristics of parametric optical frequency comb pumped with electro-optical modulated laser.

**PRINCIPLE**

Our considered OFC generator is shown in figure 1. The CW light from the laser diode is sent to an intensity modulator (IM) and modulated by a sinusoidal radio frequency (RF) signal with a frequency $f_m$. The phase modulator (PM) is also driven by the RF signal to induce positive chirp for the pulse compression. The output electrical field of the PM is described as

$$e_{OFC}(t) = E_0 \sum_{m=-\infty}^{\infty} \{ J_m(\alpha + \beta) \exp(j\theta) + J_m(-\alpha + \beta) \} \times \exp\{j[(\omega_0 + m\omega_{RF})t + \phi_{laser}(t) + m\phi_{RF}(t)]\}$$

where $E_0 \exp(j\omega_0 t)$ is the input light field, $\omega_0$ is the angular frequency of the CW laser, $\phi_{laser}(t)$ and $\phi_{RF}(t)$ are respectively the phase noise induced by the linewidth of laser and RF signal, $J_m$ is the Bessel function of the first kind and on the order of m. $\alpha$ and $\beta$ are respectively the modulation depth of the IM and PM. From Eq.(1), it can be seen that the phase noise for the m-th spectral line, $\phi_{OFC,m}(t)$ is

$$\phi_{OFC,m}(t) = m\phi_{RF}(t) + \phi_{laser}(t)$$

In the stage of pulse compression, the chirped waveform after PM is compressed in a short segment of single-mode fiber (SMF) possessing negative second-order dispersion. Subsequently, the compressed waveform enters the mixing stage with a higher peak power, allowing the mixer to operate with a correspondingly larger mixer figure of merit (FoM), defined by the product of optical power, effective interaction length and mixer nonlinearity.

In the simplest topology, two frequency non-degenerate waves propagating along the nonlinear waveguide act as parametric pumps and create new spectral sidebands. With sufficient launch power, newly created tones will grow and contribute to parametric process, generating additional high-order frequency
Consequently, parametric process in nonlinear stage results in a high-order tone count, as required for wideband frequency comb generation.

The mixing process is initiated by creation of the first-order tone possessing the phase satisfying the well-known relationship:

\[
\theta_{a_1,s_1} = 2\theta_{P_1,P_2} - \theta_{P_1,P_1}
\]  

(3)

where subscripts \( a_1 \) and \( s_1 \) represent respectively the first-order high frequency and low frequency lines. \( P_1 \) and \( P_2 \) denote two pump waves. According to Eq. (3), it leads to the scaling of phase in the higher-order four-wave mixing (FWM) components as follows:

\[
\theta_{a_{N,s_N}} = (N + 1)\theta_{P_1,P_2} - N\theta_{P_1,P_1}
\]  

(4)

When phases of the seed pumps are not correlated, the linewidth of a FWM product is inevitably broadened in configurations involving independent lasers. However, for our considered OFC generator shown in figure 1, the linewidth broadening can be eliminated. So with Eq. (1) and Eq. (4), we have

\[
\theta_N = \left[ \omega_b + \left( N + 1 \right) n - N m \right] \phi_{\text{RF}}(t) + \phi_{\text{lasers}}(t) + \left( N + 1 \right) n - N m \phi_{\text{RF}}(t)
\]  

(5)

where \( \theta_N \) is the phase of the \( N \)-th order generated comb line from \( P_m \) and \( P_n \) (power of pump comb lines). Due to the fact that \( \phi_{\text{RF}} \) is far less than \( \phi_{\text{lasers}} \), the last term in Eq. (5) can be omitted in estimating the phase noise imposed on higher-order frequency terms. So Eq. (5) clearly suggests that phase characteristics of each comb line will be preserved for the reason that the phases of two pump comb lines from the electro-optical modulated laser are correlated.

**EXPERIMENTAL SETUP**

A proof of concept experiment is performed to confirm the spectral linewidth preservation in the parametric optical frequency comb seeded with electro-optical modulated laser. The experimental setup is shown in figure 2.

A CW-laser operating at 1550.12 nm is modulated with an IM and a PM driven by a RF signal with a frequency of 10 GHz. The half-wave voltage of the IM and the PM at 10 GHz is 5.7 V and 3.5 V respectively. The IM is biased at about 2.8V to ensure it working in the linear zone. The output spectra of the IM and PM are shown in figure 3 (a) and (b).
In the experiments, the length of the SMF is 4 km, the positive chirps induced by PM and the negative second-order dispersion from SMF makes the pulse compressed. In order to enhance parametric process, an Erbium-doped Optical Fiber Amplifier (EDFA) is used to increase power inputted to the highly nonlinear fiber (HNLF). Here the amplified power is 27 dBm. The nonlinear coefficient of the HNLF is about $17 \text{ W}^{-1}\text{km}^{-1}$, and the length is 300 m. The output spectrum of the HNLF is shown in figure 4. It can be seen that more than 40 lines are generated.

To investigate the linewidth of each tone, a pulse shaper (Finisar WaveShaper 1000S) is employed as an optical band-pass filter (OBPF). One of the filtered lines is shown in figure 5.
The linewidths of the carrier, ±5th, ±10th, ±15th and ±20th tone are respectively measured with the method of delayed self-heterodyne interferometer (DSHI). In the experiment, the delayed fibre is 10km, which can ensure the relative error of the measurement below 2%. The linewidth of the carrier is measured to be 4.14MHz. Compared with the linewidth of the carrier, the measured results of the other lines are shown in figure 6. It is clear that the linewidth variation with the order of comb line is lower than 0.34 MHz. So it can be concluded that the spectral linewidth preservation is achieved.

**SUMMARY**

We have theoretically analyzed the spectral linewidth characteristics of a parametric comb. The parametric process is seeded by electro-optical modulated laser. It is found that the phase of each comb line is preserved for the reason that the phases of two pump comb lines from the electro-optical modulated laser are correlated, so the spectral linewidth of the parametric comb lines with different orders is preserved. The experiment results also confirm the conclusion.
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REFERENCES