Coherent Comb Generation With Continuous Sweep of Repetition Rate Over One-Octave

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***Abstract*— We proposed and demonstrated a coherent optical frequency comb generation with broadband continuous sweep of repetition rate based on cascaded phase and intensity modulators. Broadband phase matching between electrical drive signals applied on the cascaded phase and intensity modulators is achieved by compensating propagation delay skew between optical signal path and electrical signal path. Therefore, phase mismatch induced flatness deterioration is effectively suppressed. A flat-top 19-line optical frequency comb with repetition rate continuously sweeping over one-octave from 8.5 to 19 GHz is obtained, where the overall power deviation is <4 dB.**

***Index Terms*— Optical frequency comb, continuous-wave (CW) modulation, phase modulation, comb-spacing, continuous sweep.**

I. Introduction

STABLIZED coherent optical frequency combs (OFCs) with fixed phase relationship among a large number of comb lines have become indispensable tools in many fields. Broadband flat-top OFC with arbitrary control of the repetition rate (comb-spacing) working at tens-of-GHz-class is highly beneficial and extensively demanded for applications such as optical arbitrary waveform generation [1], [2], broadband tunable microwave photonic filters [3], atomic and molecular spectroscopy [4], precision frequency metrology [5], synchronization of independent OFCs [2] for stability evaluation and comparison [6], [7], and precise swept optical/electrical signal synthesis [8], [9].

Mode-locked laser (MLL) has been a main way to generate OFCs at hundreds-of-MHz-class repetition rates. Its repetition rate can be tuned by controlling the resonant cavity length using in-cavity tunable delay line [6] or movable mirror [10]. However, due to the sophisticated scheme for stability, these control approaches exhibit technical limitations such as narrow control range within few MHz and small servo bandwidth. Cascaded phase and intensity modulated continuous-wave (CW) laser can generate coherent OFC with repetition rate up to tens-of-GHz [11]–[14]. In order to obtain a flat-top OFC, electrical drive signals applied on the cascaded modulators should be exactly phase-matched. Therefore, continuous sweep of the repetition rate while maintaining the consistent flat-top feature brings about technical challenge for broadband phase-matching.

In this letter, we proposed and demonstrated an OFC generation scheme with broadband continuous sweep of repetition rate over one-octave based on cascaded phase and intensity modulators. By measuring and compensating the propagation delay skew between the optical signal path and the electrical signal path, broadband phase matching of the electrical drive signals applied on the cascaded modulators is thus achieved. Therefore the phase mismatch induced flatness deterioration is effectively suppressed. A 19-line OFC with repetition rate continuously sweeping over one-octave from 8.5 to 19.0 GHz in 0.5-ms sweep time is obtained. The overall power deviation of the obtained 19 comb lines is maintained within 4 dB all through the whole repetition rate sweep range.

II. Principle of Operation

The operating principle of the proposed OFC generation is outlined in Fig. 1. The output of a 1551.3-nm narrow linewidth (~15 KHz) CW distributed feedback (DFB) laser is sent through a phase modulator (PM) cascaded by an intensity modulator (IM). The electrical drive signal from a fractional-N phase-locked loop (FN-PLL) is divided to apply on the PM and IM respectively. The electrical drive signal applied on the PM is amplified to as high as about six times of the PM half-wave voltage $V_{\pi-PM}$ in order to obtain a large phase modulation index on the output lightwave signal for more comb lines. Then the obtained high-order output comb lines spaced at f_s is given by:

$$E_{PM}(t) = E_c \exp(j\omega_c t)\exp[j\pi\beta_{PM}\cos(2\pi f_s t)] \quad (1)$$

where E_c and ω_c are the amplitude and the angular frequency of the DFB laser output respectively, f_s is the frequency of the electrical drive signal, and β_{PM} is the PM electrical drive voltages normalized by $V_{\pi-PM}$.

The electrical drive signal applied on the IM is delayed by τ_E with tunable electrical delay module (TDM). The drive power is adjusted and biased appropriately after amplified to obtain a temporal pseudo-square pulse successively. Meanwhile, the phase modulated CW lightwave signal applied on the IM suffers from optical propagation delay τ_O due to fiber pigtails between the PM and IM. The propagation delay skew $\tau_S = \tau_O - \tau_E$ between the optical and electrical signal paths leads to phase mismatch between the electrical drive signals.

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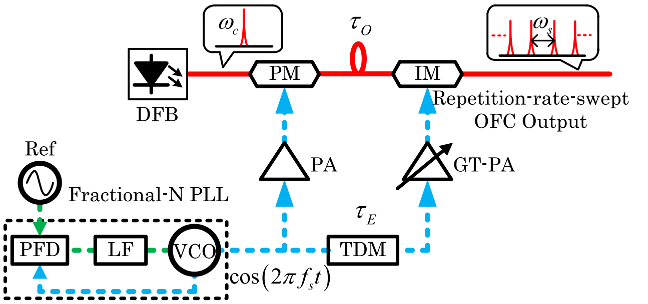

Fig. 1. Experiment setup for the repetition-rate-swept OFC generation. DFB, distributed-feedback laser; PM, phase modulator; IM, intensity modulator; PA, microwave power amplifier; GT-PA, gain-tunable microwave power amplifier; TDM, tunable electrical delay module; PFD, phase/frequency detector; LF, loop filter; VCO, voltage controlled oscillator; Ref, reference.

The output OFC shown in Fig. 1 can thus be expressed as:

$$E_{out}(t) = \frac{E_c}{2}\exp(j\omega_c t)\exp\left[j\pi\beta_{PM}\cos(\omega_s t)\right]\{1+\exp\left[j\pi(\beta_{DC}+\beta_{IM}\cos(\omega_s(t+\tau_s)))\right]\} \quad (2)$$

where $\omega_s = 2\pi f_s$ is the angular frequency of drive signal, β_{DC} and β_{IM} are the IM bias voltages and IM electrical drive voltages normalized by their half-wave voltages respectively. From (2), it is seen that the phase mismatch between the signals applied on the PM and IM is depicted as $\omega_s\tau_S$. The OFC spectra flatness is decided by β_{DC}, β_{IM} and β_{PM} after the phase alignment using phase-shifters at a single fixed repetition rate [11]–[13]. However, for broadband continuous sweep of the repetition rate, this phase-mismatch varies along with every frequency change of the electrical drive signal, resulting in flatness deterioration on the generated OFC. Thus the accurate compensation of the propagation delay skew is essential for broadband continuous sweep of the repetition rate with consistent flat-top feature.

In condition that the propagation delay skew is exactly compensated ($\tau_s = 0$), the output OFC can thus be depicted as:

$$E_{out}(t) = \frac{E_c}{2}(j)^n\exp[j(\omega_c+n\omega_s)t]\sum_{n=-\infty}^{+\infty}\{J_n(\pi\beta_{PM})+\exp(j\pi\beta_{DC})J_n[\pi(\beta_{PM}+\beta_{IM})]\} \quad (3)$$

where n is the comb line index and $J_n(x)$ stands for the n^{th} order Bessel function of first kind. The flatness feature of the obtained OFC is drive frequency (i.e. repetition rate) independent according to Eq. 3. Therefore, with appropriate initialization of β_{DC} and β_{IM} [11]–[14], the OFC flatness can be maintained while broadband continuously sweeping the repetition rate. In addition, the number of flat-top comb lines is in proportion to β_{PM}.

The principle of the measurement and compensation for the propagation delay skew is illustrated in Fig. 2. The cascaded PM and IM are driven by a square wave signal from a pulse pattern generator (PPG). A Mach-Zehnder delay interferometer (MZ-DI) with $\Delta t = 100ps$ is deployed after the PM. The output of the MZ-DI is detected by a 50-GHz balanced photo-detector, and acquired by a 60 GHz digital sampling oscilloscope. The repetition period of the square wave signal is set greater than two times of τ_O, which can be estimated by the length of pigtails. Short rise time of the square wave signal and large detection bandwidth are necessary for precise measurement. Fig. 2(b) shows the patterns when τ_S is uncompensated. There is a π-phase shift within each period of the modulated square wave signal. A 100-ps pulse of the same period as the square wave signal is generated through the MZ-DI. If τ_S is exactly compensated ($\tau_s = 0$), ideally, no π-phase shift exists within the period of square wave signal, thus no output will be observed as depicted in Fig. 2(c). However, due to the limited rise time and detection bandwidth, the pulse power is reducing along with the decrease of τ_S. The pulse power against the delay skew relative to best compensation point is shown in Fig. 2(d). Thereby, the minimum pulse power indicates the best achievable compensation of τ_S. Broadband phase matching is thus achieved.

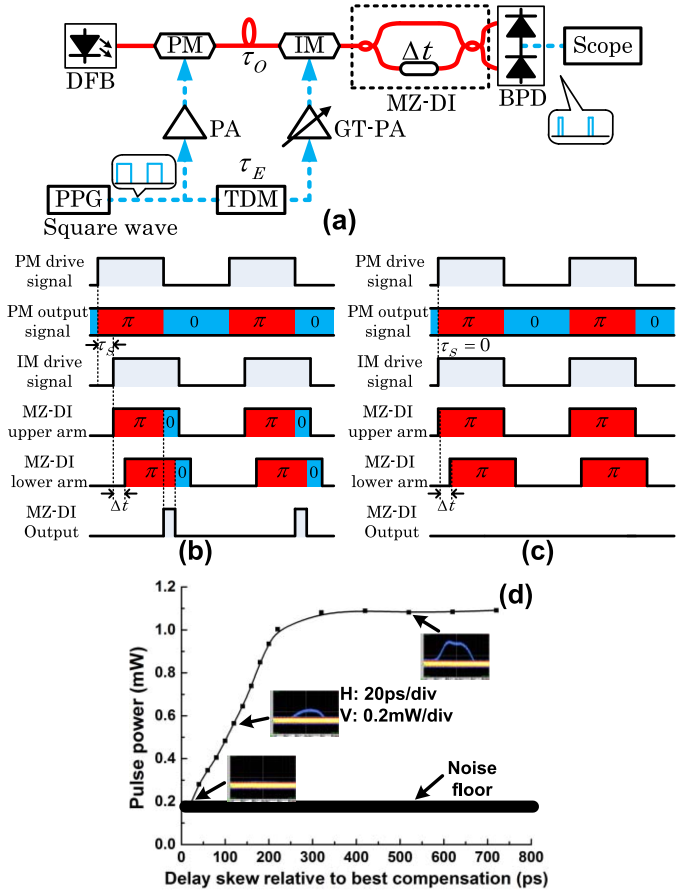

Fig. 2. (a) Propagation delay skew measurement and compensation scheme. Principle of the matching processes: (b) unmatched and (c) matched. PPG: pulse pattern generator, MZ-DI, Mach-Zehnder delay interferometer. BPD: balanced photo-detector, Scope: digital sampling oscilloscope. (d) Measured pulse power against the delay skew relative to the best compensation point.

III. Experiment Result

At the best achievable compensation point, we sweep the drive signal from 8.5 to 19.0 GHz using FN-PLL as the scheme shown in Fig. 1. Accordingly, the repetition rate of the generated OFC is broadband continuously swept following the continuous frequency sweep of FN-PLL as illustrated in Fig. 3(a). The generated OFC has 19 comb lines (from +9 to −9)

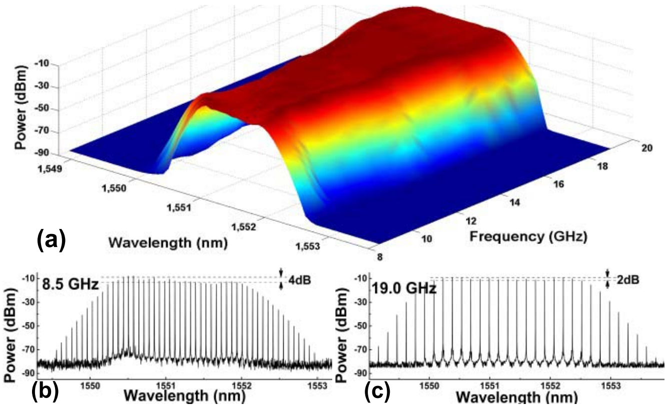

Fig. 3. (a) The spectrum of the obtained OFC with repetition rate continuously sweeping from 8.5 GHz to 19.0 GHz. Snapshots when the repetition rate is (b) 8.5 GHz and (c) 19.0 GHz.

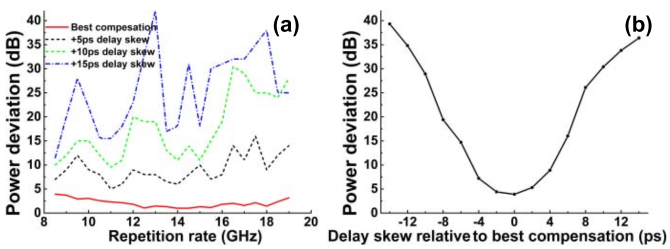

Fig. 4. Measured 19-line's overall power deviation (a) at different repetition rates; (b) against the delay skew relative to best compensation.

within 4-dB power deviation all through the whole sweep range.

Fig. 3(b) and (c) depict two snapshots for the repetition rate at lower and upper limit of 8.5 GHz and 19.0 GHz, respectively. The tone-to-noise ratio is maintained above 60 dB across the sweep range with 15-dBm output power of the DFB laser.

As observed in Fig. 4, the flatness is sensitive to the propagation delay skew between the electrical drive signals applied on the modulators. The phase-mismatch induced flatness deterioration is effectively suppressed due to the phase matching at the best compensation point as the solid line depicted at the bottom of Fig. 4(a). 5-dB overall power deviation throughout the sweep range can be obtained within ±2 ps relative propagation delay skew offset from the best compensation point.

The power deviation at the best compensation point is mainly caused by the following reasons: First, ascribing to the limited τ_S compensation resolution and TDM accuracy, the propagation delay skew cannot be exactly compensated. Thereby the optical and electrical signals are not accurately broadband phase matched. Second, the imperfect gain flatness of the PA leads to power fluctuation of the electrical drive signal which brings about deviation of modulation index against the frequency, thus deteriorates the overall flatness. In addition, due to the PA nonlinearity, the undesired harmonic components of the output within the PA bandwidth deteriorate the flatness as depicted in Fig. 4(a). Third, the nonideal frequency response of the PM and IM leads to the nonuniformity of the broadband modulation index. In other hands, by means of modifying the electrical drive signal, the flatness could be further improved [12].

Note that the sweep range is restricted by the PA bandwidth, which is 8.5–19 GHz in our experiment, and the sweep time is limited by the FN-PLL, which is 0.5 ms limited by our equipment. We believe that the sweep range can be extended by replacing with larger bandwidth PA, and the sweep time can be agilely controlled with faster FN-PLL implementations.

IV. Conclusion

In summary, OFC generation with broadband, continuous and fast sweep of the repetition rate based on cascaded phase and intensity modulators was proposed and experimentally demonstrated. A 19-line flat-top OFC with repetition rate continuously sweeping from 8.5 to 19.0 GHz in 0.5-ms sweep time is achieved by compensation of the propagation delay skew between the optical and electrical signal paths. The power deviation of the obtained 19 comb lines is maintained within 4 dB. Further works will focus on extending the sweep range and optimizing the flatness performance. These will make it a promising candidate for new applications in frequency synthesis, time/frequency metrology and arbitrary wave generation.

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