Directly Generated Gaussian-Shaped Optical Frequency Comb for Microwave Photonic Filtering and Picosecond Pulse Generation

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***Abstract*— Using only electro-optic modulators, we generate a high-quality 41-line 10-GHz Gaussian-shaped optical frequency comb. We use this comb to demonstrate apodized microwave photonic filters with a 40-dB mainlobe-to-sidelobe suppression ratio without the need of a pulse shaper. Further, our Gaussian-shaped comb has an approximately quadratic phase, which allows for compression into a high-quality pulse train via propagation in single-mode fiber.**

***Index Terms*— Filters, microwave photonics, optical signal processing, phase modulation, short pulse generation.**

I. Introduction

PHASE modulated continuous-wave (CW) laser frequency combs have seen wide use in various applications such as wavelength division multiplexing (WDM) networks [1], optical arbitrary waveform generation (O-AWG) [2], and agile arbitrary millimeter wave generation [3]. Using an optical frequency comb as a multiple carrier optical source offers new potential for achieving complex and tunable microwave photonic filters [4], [8]. For example, in [4] we used a line-by-line pulse shaper to apodize the optical power spectrum into a Gaussian shape, resulting in a Gaussian RF filter shape. Although direct generation of flat-topped optical frequency combs [5], [6] has drawn much attention, little work has been done to directly generate Gaussian-shaped optical frequency combs. In one report, Hisatake et al. demonstrated Gaussian-shaped comb generation based on spatial convolution of a slit and a periodically moving optical spot in a system based on electro-optic deflectors [7]. In [8], we generated approximately Gaussian-shaped frequency combs using only electro-optical modulators driven by sinusoidal phase. However, because the resulting comb was not very smooth, a further nonlinear optics spectral smoothing stage was needed to achieve high quality RF photonic filter shapes. In our current experiment, we adopt a tailored RF drive approach [5] to directly generate a high quality Gaussian-shaped comb (37 lines closely matched to a Gaussian shape across a dynamic range of 20 dB out of a total of 41 lines). With this comb, we implement RF filters with 40-dB mainlobe-to-sidelobe suppression ratio (MSSR). The MSSR is improved compared to that reported in [4], and without the need for a high resolution pulse shaper, the set-up is much more compact. Furthermore, since the spectral phase of the generated Gaussian comb is almost purely quadratic, short pulse generation can be achieved simply by propagation in dispersive fiber.

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II. Principle of Microwave Photonic Filters

Fig. 1 shows the experimental setup of the 10-GHz Gaussian-shaped comb generator, which consists of three IMs and two PMs. We operate the RF oscillator at 10 GHz. At 10 GHz, the V_π is ∼9 V for the IM's and ∼3 V for the PM's. The RF voltages delivered to IM1 and IM2 are both 0.5 V_π zero to peak, and the RF voltage to IM3 is V_π. We cascade two phase modulators at their maximum RF input power (30 dBm) to double the total modulation index seen by the pulse and increase the number of comb lines.

The Gaussian-shaped comb generation mechanism is based on time-to-frequency mapping theory, where quadratic and periodic temporal phase causes the spectral envelope to mimic the input intensity profile to the phase modulators [9]–[11]. So for generating a Gaussian-shaped comb, the following two requirements should be met:

1) Apply a quadratic phase. Applying a purely quadratic, periodic temporal phase is difficult, so here we apply a "quasi-quadratic" phase by combining the first and second harmonic of the sinusoidal drive signal with a power ratio of 24-dB and phase shift of 180° selected to suppress the 4th order term of the cosine expansion of the phase-refer to the red dashed box in Fig. 1. This substantially improves the approximation to the target quadratic phase profile [5], [11].

2) Generate a Gaussian-shaped pulse. IM1 and IM2 are both biased at 0.5 V_π with RF drive amplitude 0.5 V_π. IM3 is biased at 0 (maximum transmission) with RF drive amplitude V_π. The pulse profile with each modulator has been shown in Fig. 2(a). We can get a very close approximation to a Gaussian pulse with the series combination of all three IMs as shown in Fig. 2(b). Fig. 2(c) and (d) show the simulated comb

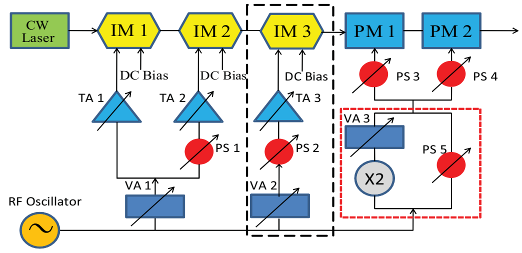

Fig. 1. Experimental setup for Gaussian-shaped comb generation. TA: tunable amplifier. VA: variable attenuator. PS: phase shifter. Red dashed module: quasi-quadratic phase generation.

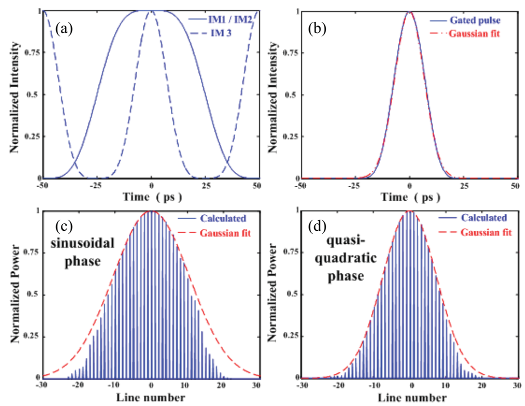

Fig. 2. Simulation results. (a) Solid blue line: pulse profile with either IM1 or IM2 alone. Dashed blue line: pulse profile with IM3 alone. (b) Solid blue line: Gaussian pulse expected from the series combination of IM1, IM2, and IM3. Dashed red line: Gaussian fit. (c) Simulated comb spectrum driven by sinusoidal phase with Gaussian fit. (d) Simulated Gaussian-shaped comb spectrum driven by quasi-quadratic phase with Gaussian fit.

spectra driven by sinusoidal phase and quasi-quadratic phase with Gaussian fits respectively. The use of quasi-quadratic phase improves the performance of Gaussian-shaped comb generation significantly over the sinusoidal phase.

III. Frequency Domain Application for Microwave Photonic Filtering

We employ the directly generated Gaussian-shaped comb as a multiple carrier optical source for RF photonic filtering and shape the filter pass bands. Fig. 3 shows our RF photonic filtering setup. The comb is single-sideband modulated in a dual drive Mach–Zehnder modulator biased at the quadrature point and driven by a pair of RF signals with a 90 degree phase difference. The modulator output is sent through a dispersion compensating fiber (DCF) with specified dispersion of -1259.54 ps/nm at 1550 nm and relative dispersion slope (the ratio of dispersion slope to dispersion at 1550 nm) of 0.00455/nm, resulting in 96-ps relative tap delay between adjacent 10 GHz comb lines. The optical output signal, after being amplified by an EDFA is detected by a 22 GHz bandwidth photodiode and measured by a network analyzer over a span of 300 kHz-20GHz. The filter transfer function can be written as [4]

$$H(\omega_{\mathrm{RF}}) \propto \sum_{n=0}^{n=N-1} a_n^2 e^{jnD2\pi\,\Delta f\,\omega_{\mathrm{RF}}} \tag{1}$$

where N is the total number of the taps, a_n^2 is the optical intensity of the n^{th} tap, D is the fiber dispersion, Δf is the repetition frequency of the optical comb, 10 GHz in our experiment, $2\pi D\Delta f$ is the tap delay between two adjacent taps, 96-ps in our experiment. The free spectral range (FSR) is the inverse of the tap delay, which can be tuned by changing the length of DCF.

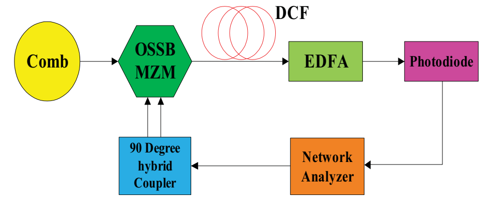

Fig. 3. Experimental setup of the microwave photonic filter based on Gaussian-shaped frequency comb. DCF: dispersion compensating fiber. OSSB MZM: optical single-sideband Mach–Zehnder modulator.

Fig. 4 shows the experimental results. First, we turn off TA3 (in Fig. 1). Fig. 4(a) shows a 50-line 10-GHz flat-topped optical frequency comb spectrum measured at the photodiode (in Fig. 3). After turning on TA3, Fig. 4(b) shows a 41-line 10-GHz Gaussian-shaped optical frequency comb spectrum measured at the photodiode; the EDFA is adjusted to set the average power at the photodiode to 4.3 dBm, as used with the flat-topped comb. The standard deviation of the comb line amplitudes from a best-fit Gaussian profile is 0.42 dB for the central 37 lines and 0.26 dB for the central 35 lines, with an excellent match over 37 spectral lines across a 20-dB dynamic range. After applying the comb to our filter setup, we measured the filter transfer function with a network analyzer. We compare our experimental results, adjusted an RF calibration factor which accounts for high frequency roll-off due to cable loss and modulator and photodiode frequency response, with simulation. The RF calibration data can be obtained by measuring the link frequency response without the dispersion compensating fiber [4]. Fig. 4(c) shows the measured (blue, after calibration) and simulated (red) filter transfer functions using the flat-topped comb. At baseband, the filter has a 3-dB bandwidth of 116 MHz, with 16.2 dB MSSR. The passband at 10.4 GHz has a 3-dB bandwidth of 255 MHz with 14.2 dB MSSR. Modeling (based on the measured optical power spectrum) indicates the filter has a 3-dB bandwidth of 130 MHz and 262 MHz with 15.8 dB MSSR at both baseband and passband, in very close agreements with our experiment. Fig. 4(d) shows the measured (blue) and simulated (red) filter transfer functions using the above Gaussian-shaped comb. At the baseband, the filter has a 3-dB bandwidth of 186 MHz, with 40 dB MSSR. The 10.4 GHz passband has a 3-dB bandwidth of 355 MHz with 33.7 dB MSSR. Modeling indicates the filter has a 3-dB bandwidth of 210 MHz and 420 MHz with 36.6 dB MSSR at both baseband and passband, in very close agreements with our experiment. The filter FSR is determined by the length of DCF fiber. By adding or decreasing the length of DCF we can change FSR, and vary the filter pass band center frequency accordingly.

IV. Time Domain Application for Short Pulse Generations

In addition to frequency domain applications such as microwave photonic filtering, our Gaussian-shaped optical

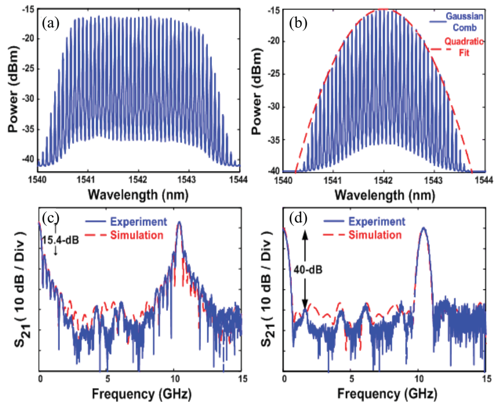

Fig. 4. Experimental results. (a) Flat-topped comb on a log scale. (b) Gaussian-shaped comb on a log scale. (c) Measured (blue line) and simulated (red line, after calibration) RF photonic filter transfer functions with flat-topped comb in (a). (d) Measured (blue line, after calibration) and simulated (red line) RF photonic filter functions with Gaussian-shaped comb in (b).

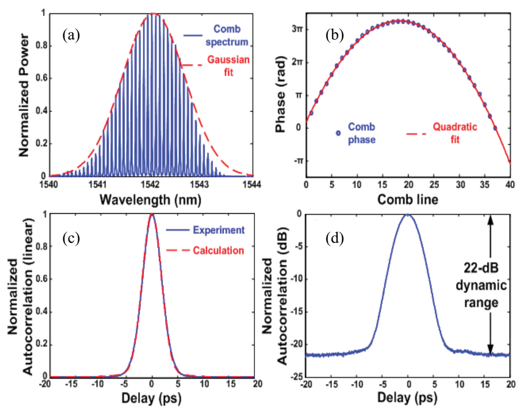

Fig. 5. Experimental results. (a) Gaussian-shaped comb on a linear scale (blue line) and Gaussian fit (red line). (b) Measured spectral phase (blue line) and quadratic fit (red line). (c) Time domain intensity autocorrelations of the output pulse obtained after comb propagates through ~740 m of SMF (blue line) and calculated autocorrelation trace taking the comb spectrum (a) and assuming a flat spectral phase (red line). An excellent agreement is seen between the two. (d) Experimental intensity autocorrelation on a log scale which shows 22 dB dynamic range.

frequency comb is suitable for generation of trains of high quality picosecond pulses. Figure 5(a) shows the Gaussian-shaped optical frequency comb spectrum on a linear scale; again the shape agrees very well with the Gaussian fit. Figure 5(b) shows the spectral phase of the comb (blue) measured using a linear optical implementation of spectral shearing interferometry [12]. The phase has a quadratic nature (red), as expected. This indicates pulse compression can be accomplished using the appropriate length of single-mode fiber (SMF). The blue solid curve in Fig. 5(c) shows on a linear scale the measured intensity autocorrelation of the output pulse after passing the comb in Fig. 5(a) through 740 meter of SMF. The theoretical intensity autocorrelation (red dashed curve) taking into account the measured comb spectrum and assuming a flat phase is plotted as well. The excellent agreement between the two curves indicates high-quality pulse compression to the bandwidth-limit duration. The measured autocorrelation trace has 4.35 ps FWHM, corresponding to a 3.1 ps pulse width assuming a Gaussian pulse shape. Figure 5(d) shows the experimental intensity autocorrelation trace on a log scale. The pulse shows a 22-dB dynamic range with respect to the background, which is attributed to amplified spontaneous emission background from the EDFA.

V. Conclusion

We introduce a high quality 10-GHz Gaussian-shaped optical frequency comb generation (37 lines across a 20 dB dynamic range out of a total 41 lines) using only electro-optic modulators with quasi-quadratic phase [5] for improved time-to-frequency mapping [8]–[11]. Based on this directly generated Gaussian-shaped optical frequency comb, we demonstrate 40-dB MSSR microwave photonic filters. Because a line-by-line pulse shaper is no longer required, the experimental implementation is greatly simplified. The filter FSR can be tuned by changing the length of DCF. Also our directly generated Gaussian-shaped comb is fully compatible with the novel tuning approach, based on varying optical delay in an interferometer structure, demonstrated in [4]. Based on the Gaussian-shaped comb, we have also demonstrated high quality short pulse generation with 3.1 ps pulse width assuming a Gaussian pulse shape and intensity autocorrelation with 22-dB dynamic range.

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