Generation of very flat optical frequency combs from continuous-wave lasers using cascaded intensity and phase modulators driven by tailored radio frequency waveforms

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We demonstrate a scheme based on a cascade of lithium niobate intensity and phase modulators driven by specially tailored RF waveforms to generate an optical frequency comb with very high spectral flatness. In this Letter, we demonstrate a 10 GHz comb with 38 comb lines within a spectral power variation below 1 dB. The number of comb lines that can be generated is limited by the power handling capability of the phase modulator, and this can be scaled without compromising the spectral flatness. Furthermore, the spectral phase of the generated combs in our scheme is almost purely quadratic, which, as we will demonstrate, allows for high-quality pulse compression using only single-mode fiber.

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Strong sinusoidal phase modulation of a CW laser creates multiple sidebands, leading to generation of a frequency comb [1]. Advantages of this technique include the ability to create high repetition rate combs with stable optical center frequencies given by the source laser and convenient tuning of the repetition rate and optical center frequency. Therefore, such combs are a source of choice for some applications in optical communications [2], RF photonics [3], and optical arbitrary waveform generation [4]. However, by phase modulation alone, the spectral flatness of the comb is quite poor with significant line-to-line amplitude variations.

A flat frequency comb is generally desired. For example, if the comb is used as a multiwavelength source, it is desirable to have equal power in different wavelengths. For applications such as RF photonic filtering requiring a specific spectral shape [5], apodization is much easier with minimal excess loss if we start off with a flat comb. Also, for time domain applications where a short pulse is needed, abrupt comb line-to-line variations result in poor pulse quality. Some examples of recent research activity based on modulation of a CW laser aimed at generating flatter combs can be found in [6–10]. Though all of these schemes improve the flatness significantly compared to phase-only modulation, they still provide either limited flatness over the bandwidth of interest or a limited number of comb lines over which flatness can be maintained. For example, in [7] the comb shows a 7 dB power variation over the ~60 comb lines that constitute the flat region of the spectrum, while [8,9] report 11 comb lines, with a 1.1 dB and 1.9 dB power variation, respectively. In this Letter, we demonstrate a scheme to achieve very flat combs using a cascade of intensity and phase modulators driven by tailored RF waveforms. In particular, we report a 10 GHz comb with 38 comb lines in a 1 dB bandwidth and ~60 comb lines above the noise floor of the optical spectrum analyzer (60 dB bandwidth). The number of comb lines can be scaled by increasing the RF drive power without sacrificing spectral flatness. Also, the spectral phase of the comb generated in our experiment is almost purely quadratic, which allows for generation of high-quality pulses via compression in a simple dispersive fiber or chirped fiber Bragg grating.

Our research draws on the interesting theoretical work of Torres-Company *et al.* [11], which proposed a novel way of understanding the spectral flatness achieved in previous schemes such as [6,7]. When a flat-topped pulse is subjected to a strong, periodic, quadratically varying temporal phase, it undergoes time-to-frequency mapping [12,13], resulting in a flat comb due to the shape being similar to the time domain intensity of the input waveform. A convenient approach to generate flat-topped pulses is to use an intensity modulator driven with a sinusoid with an amplitude $V = V_\pi/2$ of the modulator and a DC bias corresponding to a phase shift of $\phi_{\mathrm{dc}} = -\pi/2$ [the envelope of the output field after the intensity modulator is given by the relation $(1 + \exp(j\phi_{\mathrm{dc}})\exp(j\pi V/V_\pi \cos\omega_{\mathrm{rf}}t))$, which in our case, after substitution simplifies to $(1 + \exp(-j\frac{\pi}{2})\exp(j\frac{\pi}{2}\cos\omega_{\mathrm{rf}}t))$]. Generating a periodic quadratic temporal phase, though, is hard; however, a sinusoidal temporal phase can be approximated by a quadratic function around its peak or its valley and to a first order provides a means to generate the required quadratic temporal phase. Figure 1(a) shows this scheme combining the two aspects, and Fig. 1(b) shows the spectrum simulated assuming the phase modulator is driven with a sinusoidal voltage whose amplitude V satisfies the relation $\pi V/V_\pi = 20$ [i.e., the effect of the phase modulator can be written as a multiplication by $\exp(j\pi V/V_\pi \cos\omega_{\mathrm{rf}}t) = \exp(j20\cos\omega_{\mathrm{rf}}t)$]. In Fig. 1(b) we see a flat central section to the spectra, but toward the edges there are pronounced "bat ears." To understand this, we look at Fig. 1(c) (blue solid curve), which shows the time domain signal, and Fig. 1(c) (red solid curve), which shows the sinusoidal temporal phase. In the central part, the time domain signal is very flat and the phase is almost quadratic, leading to good spectral flatness. As we move away from the center and the phase starts deviating from a quadratic, the

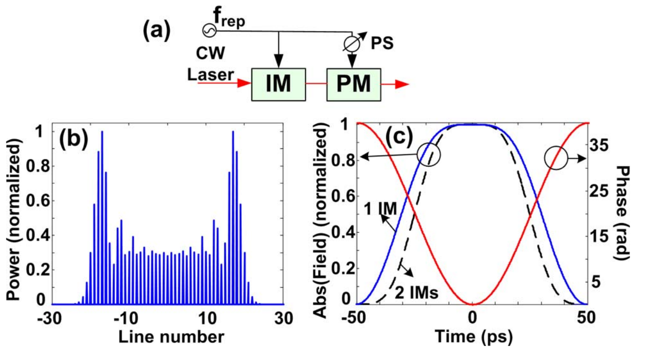

Fig. 1. (Color online) (a) Experimental scheme for flattening frequency combs generated by phase modulation using the cascaded intensity modulator (IM) and phase modulator (PM): PS, RF phase shifter. (b) Simulated output spectrum for this scheme. (c) Time domain plot showing the temporal phase applied by the PM (red solid curve) to the outputs after one IM (blue solid curve) and two IMs (black dashed curve).

flatness is degraded. The strong peaks or bat ears occur at the spectral extrema where the instantaneous frequency, i.e., the time derivative of the temporal phase, is at a minimum or maximum. The bat ears may be explained on the basis of the relatively long time for which the instantaneous frequency function dwells at the frequency extrema [14].

To obtain flat spectra, we need both a nice flat-topped pulse as well as a good quadratic temporal phase. Accordingly, we propose two modifications to the above method. A first improvement would be to make the flat-topped pulse sharper, which will reduce the fraction of the waveform seeing a significant departure from the quadratic temporal phase. This can be achieved using two intensity modulators in series driven with the same parameters as described previously. Figure 1(c) (black dashed curve) shows the new sharper time domain waveform. Secondly, because the bat ears happen due to deviation from quadratic phase, we attempt to generate a phase profile that better approximates a quadratic. The expansion for the cosine around its maximum up to the first undesirable term is

$$\cos(\omega_{\rm rf}t) = 1 - \frac{(\omega_{\rm rf}t)^2}{2!} + \frac{(\omega_{\rm rf}t)^4}{4!} - \ldots, \tag{1}$$

so we have

$$\cos(\omega_{\rm rf}t) - \frac{1}{16}\cos(2\omega_{\rm rf}t) = \frac{15}{16} - 0.75\frac{(\omega_{\rm rf}t)^2}{2!} + 0 + \ldots. \tag{2}$$

From Eq. (2) we see that by using the first and second harmonics (which can be easily generated with a ×2 frequency multiplier) with a suitable ratio and phase shift between them, the fourth-order term (which is the first nonideal term) can be made zero. With regard to higher-order terms, because the cascade of the intensity modulators creates a waveform with a sharper decay, they are less of an issue in the region of the flat-topped pulse. Figure 2(a) shows the scheme incorporating both the improvements we discussed. A tunable attenuator adjusts the ratio between the fundamental harmonic and the second harmonic to the required value [$(1/16)^2 \sim -24$ dB], and a tunable RF phase shifter ensures that they are 180° out of phase as required. We also have other tunable RF phase shifters to ensure that there is a timing match between the different components. Figure 2(b) shows the simulated spectrum, which is now significantly flattened, with the absence of any bat-ear shape. In our actual experiment, a minor difference to the scheme shown in Fig. 2(a) is that we use two phase modulators in series instead of one. This is a common technique used (e.g., [7]) to overcome the RF power handling limit of the phase modulators. In our case we drive each phase modulator by its maximum RF power of 1 W; driving two phase modulators identically allows greater power handling and doubles the number of comb lines. The IM we use has a V_π of ~8 V, the PM has a V_π of ~3 V, and all modulators are pigtailed with polarization-maintaining fiber. The frequency of the RF oscillator is 10 GHz. The net optical loss of the whole apparatus is ~15 dB (the unavoidable loss due to gating of the CW by the intensity modulators is only ~4 dB, while the rest is mainly modulator insertion losses). Figures 2(c) and 2(d) show the experimental output comb spectra in linear and log scale, respectively. We observe a very flat spectral profile with 38 comb lines in a 1 dB bandwidth ($< \pm 10\%$) [circled in Fig. 2(d)] with much smaller variations in smaller bandwidths around the center.

Another interesting aspect is that, in the large phase modulation limit, a waveform with a pure quadratic temporal phase corresponds to a spectrum with a pure quadratic phase. This, in turn, corresponds to a pulse with a linear chirp, which can be compressed to the bandwidth limit with high quality just using an appropriate length of standard single-mode fiber [(SMF) compared to more complex pulse shaper based methods [15]]. For the bandwidths involved, the effect of the dispersion slope of the fiber is small. Figure 3(a) (blue solid curve), which shows

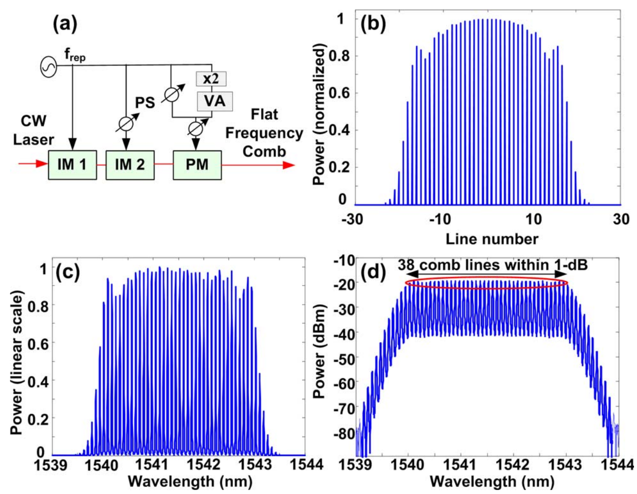

Fig. 2. (Color online) (a) Experimental scheme for comb generation with high spectral flatness: VA, variable attenuator; PS, RF phase shifters (in our actual experiment, we use two PMs in series to generate a greater number of lines). (b) Simulated output spectrum in this case. (c), (d) Output spectra of the experimentally generated comb in linear and log scale showing 38 comb lines within a 1 dB variation.

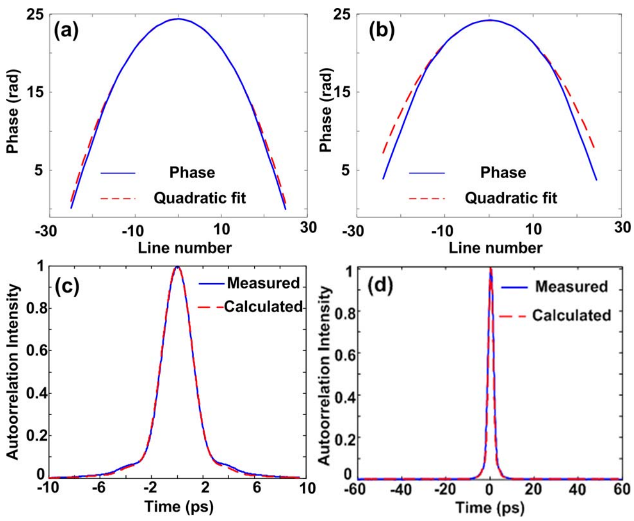

Fig. 3. (Color online) (a), (b) Simulated spectral phase and the quadratic fit to it for the case of phase modulation with tailored RF waveform (a) and a sinusoid (b). (c), (d) Short- and long-aperture time domain intensity autocorrelations of the output pulse [(measured, blue solid curve) obtained after comb propagation through ~850 m of SMF] superimposed with the autocorrelation calculated taking the spectra [Fig. 2(c)] and assuming a flat spectral phase. A very good agreement is seen between the two.

the simulated spectral phase of the comb together with a quadratic fit (red dashed curve), clearly indicates this by showing an excellent agreement between them. This idea was first discussed in [16], and the process of making the drive more quadratic is referred to as the aberration correction. To demonstrate its superiority over a pure sinusoid, Fig. 3(b) shows the simulated spectral phase for the same configuration with the phase modulator now driven by a pure sinusoid. In this case, the spectral phase of the comb differs more significantly from a quadratic; this is expected to translate into lower quality pulse compression.

We measured the spectral phase of the comb using our frequency comb characterization technique based on a linear implementation of spectral shearing interferometry, described in detail in [17]. The measured phase indicated that pulse compression could be accomplished using ~850 m of SMF. Figures 3(c) and 3(d) (blue solid curve) show the measured intensity autocorrelation of the pulse resulting after fiber propagation in a short and wide temporal window. The theoretical intensity autocorrelation (red dashed curve) taking into account the measured comb spectrum and assuming a flat phase is also plotted. We see excellent agreement, indicating high-quality pulse compression to a bandwidth-limited pulse. The obtained pulse has an intensity autocorrelation FWHM of ~2.8 ps, which corresponds to an intensity FWHM of ~2.1 ps, assuming the sinc^2 intensity profile is appropriate for the nearly flat-topped spectrum.

In summary, we have demonstrated a new, easily scalable scheme for generating very flat optical frequency combs using cascaded intensity and phase modulators driven by tailored RF waveforms. In this Letter we demonstrated a 10 GHz comb with 38 comb lines in a 1 dB bandwidth and around 60 comb lines in total. Another attractive aspect of our scheme is the ability to achieve very high-quality compression (in our experiments resulting in a ~2.1 ps bandwidth-limited pulse) simply through propagation in standard SMF.

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