Supercontinuum Generation by Saturated $\chi^{(2)}$ Interactions

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Abstract: We establish a model for supercontinuum generation in dispersion-engineered $\chi^{(2)}$ nanowaveguides based on saturated second-harmonic generation, and show that this process exhibits favorable scaling laws when compared to approaches based on $\chi^{(3)}$ nonlinearities.

Introduction.— The generation of coherent supercontinua from mode-locked lasers is an increasingly critical nonlinear process found in many modern optical systems. Typical approaches to supercontinuum generation (SCG) rely on self-phase modulation (SPM) due to $\chi^{(3)}$ interactions in highly nonlinear fibers or in nanophotonic waveguides. This process requires pulse energies on the order of 10's - 100's of pJ, with state-of-the-art devices utilizing the $P_{\text{SCG}} \propto L^{-1}$ scaling of the required power with device length L to operate with 10's of pJ [1]. When used for carrier-envelope-offset frequency (f_{ceo}) detection, nonlinear waveguides are used to frequency double the long-wavelength portion of the supercontinuum to overlap with shorter wavelengths and generate an f-2f beatnote [2,3]. However, all of these approaches to f-2f detection typically produce a narrowband second harmonic (SH), which limits the amount of generated photocurrent since only a small fraction of the available power spectrum is used. At this time, a number of applications would benefit both from lower energy requirements and from more efficient f_{ceo} detection to enable the generation and stabilization of compact, high repetition rate frequency combs [1].

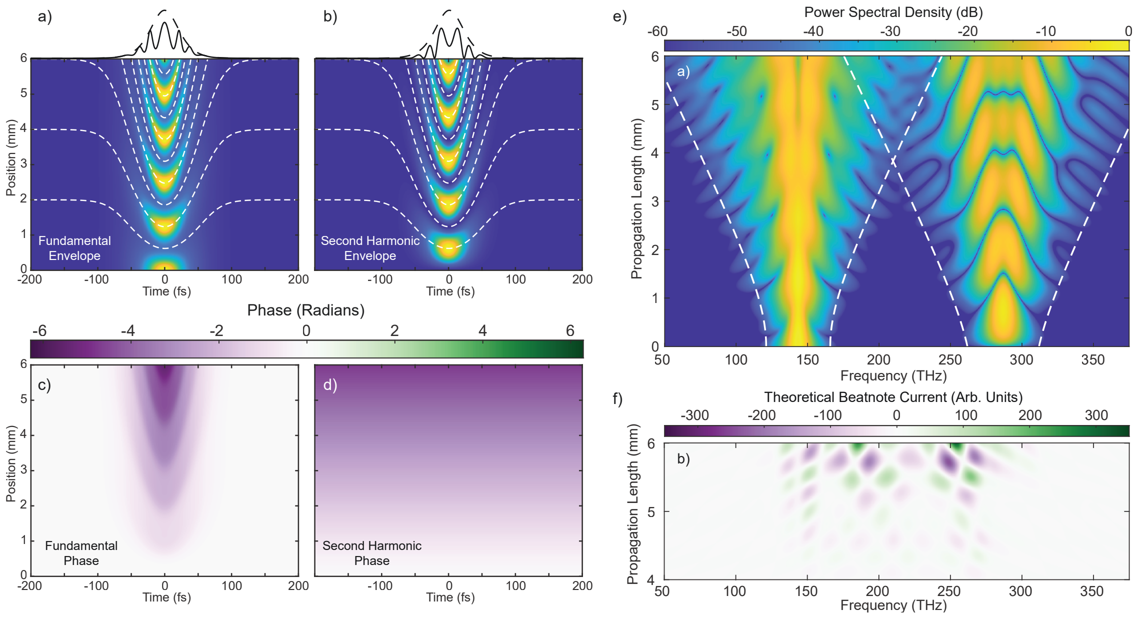

Fig. 1. a,b) Theoretical evolution of the FH and SH envelopes, $|A_\omega|^2$ and $|A_{2\omega}|^2$. The variation of the conversion half-period (dashed white) across the pulse results in rapid temporal variation in the pulse envelopes (solid black). c,d) Phase of the fundamental and second harmonic. e) Spectral broadening of the two harmonics due to the femtosecond-scale amplitude modulations. f) Theoretical beatnote photocurrent as a function of frequency and propagation length. The beatnotes periodically fall in and out of phase during propagation, and may remain in phase across 100's of nm of bandwidth.

Recent work has reported experimental results for ultra-low power SCG in dispersion engineered TFLN waveguides [4]. Here we present a model of the quasi-static nonlinear dynamics involved that quantitatively accounts for the experimental results, and establishes the relevant scaling laws for this process. The approach considered here assumes that the waveguide geometry can be chosen to make dispersion negligible and that second-harmonic generation (SHG) is driven into saturation. This process generates coherent octaves of bandwidth simultaneously for both the fundamental (FH) and SH by introducing rapid amplitude modulations onto the pulse envelopes associated with each harmonic. In contrast with devices based on $\chi^{(3)}$ interactions, saturated SHG exhibits a $P_{\mathrm{SCG}} \propto L^{-2}$ scaling of the power requirements with device length and $P_{\mathrm{SCG}} \propto \tau^{-3}$ scaling with pulse duration. For realistic numbers, this process may realize coherent octaves of bandwidth with picojoules, or even femtojoules, of pulse energy. We validate the analytical models proposed here experimentally and find strong agreement between theory and experiment, thereby establishing this approach as a practical route toward low-power SCG.

Results.— In the absence of dispersion each time slice of the pulse evolves in the same way as a CW wave of the same intensity, so the instantaneous power $|A(z,t)|^2$ of the FH and SH formed by saturated SHG can be found in terms of Jacobi-Elliptic functions, $|A_\omega(z,t)|^2 = (1-\eta^2(z,t))|A_\omega(0,t)|^2$, and $|A_{2\omega}(z,t)|^2 = \eta^2(z,t)|A_\omega(0,t)|^2$, where the instantaneous field conversion efficiency is given by $\eta(z,t) = \nu(t)\mathrm{sn}\left(\kappa A_\omega(0,t)z/\nu(t)|\nu^4(t)\right)$. Here sn is the Jacobi elliptic sine and $\nu(t) = -|\Delta k/(4\kappa A_\omega(0,t))| + \sqrt{1+|\Delta k/(4\kappa A_\omega(0,t))|^2}$, and $\nu^2(t)$ represents the maximum pump depletion attainable as a function of the local field amplitude $A_\omega(0,t)$. During propagation, each time slice of the FH is depleted and regenerated with a different spatial half-frequency (Fig.1(a,b), dashed white lines). This results in saturation-induced amplitude modulations (Fig.1(a,b), solid black lines), which spectrally broaden both harmonics. Here, we have assumed a 50-fs-wide pump pulse with an energy of 4 pJ, a normalized efficiency of $\eta_0 = 1000$ %/W-cm^2, and $\Delta k = -3\pi/L$, where L is the length of the waveguide. We note here that the phase of the two harmonics (Fig.1(c,d)) saturates and does not contribute meaningfully to spectral broadening. Figures 1(e,f) show the generated power spectral density and beatnote current generated by the overlapping harmonics. In principle, the 6-mm-long waveguide considered here spectrally broadens the two harmonics enough to produce beatnotes from 1 to 2 μm. Remarkably, these beatnotes can remain in phase across the entire overlap region, resulting in bright f-2f beatnotes without narrowband filtering.

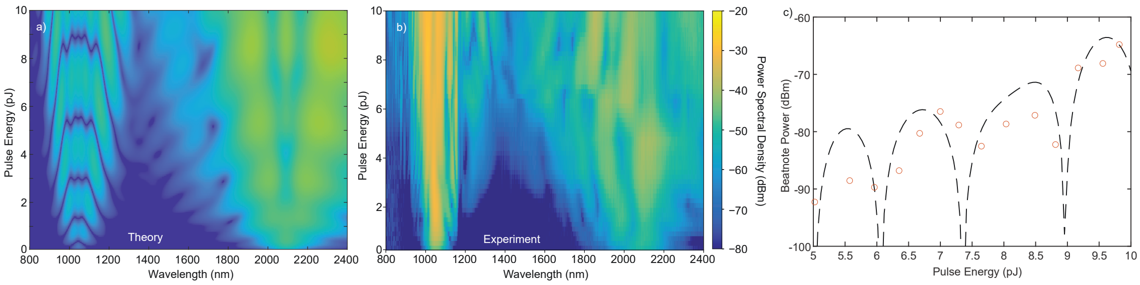

Fig. 2. a) Theoretical and b) measured power spectral density output from the waveguide as a function of power. c) f-2f beatenote current as a function of power.

We validate this heuristic model using the same waveguides and experimental setup as [4]. The calculated and measured power spectral density of the two harmonics as a function of pulse energy input to the waveguide is shown in Fig. 2(a) and 2(b), respectively. The experimental conditions considered here are identical to those of Fig. 1, with the power varied from 0.5 to 10 pJ. We observe strong agreement between theory and experiment, with the two spectra merging at the -60 dB level with pulse energies as low as 2 pJ. Figure 2(c) shows the calculated (orange circles) and measured (dashed black) beatnote power as a function of pulse energy. We observe oscillations in the photocurrent with increasing pump pulse energy due to the quasi-periodic re-phasing of the f_{ceo} beatnotes and observe that for a suitable choice of pulse energy, e.g. 5.5-, 6.5-, 8.5-, and 9.5-pJ, the f_{ceo} beatnotes remain in phase across the 400-nm-wide detection bandwidth, resulting in local maxima.

Conclusion.— We have proposed and experimentally validated a new approach to SCG and carrier-envelope-offset detection based on saturated SHG in a dispersion-engineered PPLN waveguides. These waveguides achieve multi-octave SCG by introducing femtosecond-scale amplitude modulations to the field envelopes due to temporal variations of the conversion period. The resulting spectra overlap and produce f_{ceo} beatnotes that remain in phase across a broad bandwidth, thereby enabling efficient f_{ceo} detection with low pulse energies.

References

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