Ultrafast Temporal Phase Detection Using Thick Nonlinear Crystals

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Abstract: We experimentally demonstrated that second-harmonic generation yield due to a thick nonlinear crystal is sensitive to temporal phase of ultrashort pulses, which could be useful in temporal chirp monitoring and ultrafast coherent communications.

OCIS codes: (320.0320) Ultrafast Optics; (230.4320) Nonlinear optical devices

1. Introduction

There exist many techniques able to retrieve intensity and phase profiles of ultrafast optical waveforms, however, they usually involve elaborate setup and/or intensive computation [1, 2, 3]. For some applications, such as optimization of femtosecond oscillators or amplifiers, simple techniques to quickly diagnose and minimize pulse widths and phase distortions (i.e., chirp) are sufficient. In the presence of a broad phase-matching (PM) bandwidth, second-harmonic generation (SHG) yield is sensitive to pulse width and has been used to monitor the fast change of spectral phase [4]. This scheme fails to detect pure temporal phase distortion, such as induced by self-phase modulation (SPM) in a Kerr medium. A limited number of techniques have been developed to directly measure the temporal phase profile [5, 6] or asses the degree of temporal chirp [7, 8]. However, the corresponding update speeds are limited by the data acquisition and post-processing in software (slower than tens of hertz). Diagnosis of spectral broadening due to temporal phase modulation by measuring the power of newly generated spectral components can achieve fast updates, but may suffer from poor sensitivities at small chirp. In this work, we experimentally demonstrated a new scheme to detect the temporal phase distortion using SHG yield due to narrow PM bandwidth. The update speed is limited by the photodetector bandwidth (can be tens of GHz), which could be useful in ultrafast coherent communications.

2. Theory

Consider a pulse of complex temporal envelope $a(t)=\sqrt{I(t)}e^{j\phi(t)}$. The corresponding nonlinear polarization spectrum in the second-harmonic (SH) band is: $P_{NL}(\omega)=F\{a^2(t)\}$. The complex SH spectral envelope arising from a thick nonlinear crystal with a PM spectrum much narrower than $P_{NL}(\omega)$ can be approximated by: $A_{2\omega}(\omega)\propto P_{NL}(0)\delta(\omega)$. The average SH power is proportional to the integral of $|A_{2\omega}(\omega)|^2$:

$$\langle P_{2\omega}\rangle \propto \left|\int_{-\infty}^{\infty} I(t)e^{j2\phi(t)}dt\right|^2 \tag{1}$$

Unlike the case of broadband SHG where $\langle P_{2\omega}\rangle \propto \int_{-\infty}^{\infty} I^2(t)dt$, Eq. (1) is sensitive to the temporal intensity and phase simultaneously. For example, the narrowband SHG yield of a linearly chirped Gaussian pulse $a(t)\propto e^{-(1-jC)t^2/\tau^2}$ scales with the temporal chirp parameter C in the form of: $(1+C^2)^{-1/2}$. A unit-step $\phi(t)$ with a $\pi/2$-phase jump occurring at the center of a symmetric $I(t)$ can even "turn off" the output of narrowband SHG, which can be used in binary coding of ultrafast coherent communications.

3. Experimental results

For lack of a temporal phase modulator with sub-picosecond response, we used SPM in highly nonlinear fiber (HNLF) at different input powers to generate different temporal phases. The experimental setup is shown in Fig. 1. A passively mode-locked Er-doped fiber laser produced 50 MHz, 300 fs pulses at 1560 nm. A section of dispersion compensating fiber is used to minimize the pulse width before entering the 15-meters-long HNLF with group velocity dispersion parameter β_2=0.28 ps^2/km and Kerr nonlinear coefficient γ=10 W^{-1}/km. For coupled powers larger than ~100 μW, the length of the HNLF (15 m) is longer than the nonlinear length and much shorter than the dispersion length (116 m) [9]. Pulse propagation under this condition is dominated by the SPM-induced temporal phase distortion, while the pulse width remains unchanged. The temporally chirped pulse at the output of the HNLF was coupled into a 5-cm-long periodically poled lithium niobate

(PPLN) waveguide with a ~50 GHz PM bandwidth for narrowband SHG [3], then detected by a photomultiplier tube and lock-in amplifier. The fundamental power and spectral intensity were monitored by a power meter and an optical spectrum analyzer to compensate for the source fluctuation and diagnose the SPM strength, respectively.

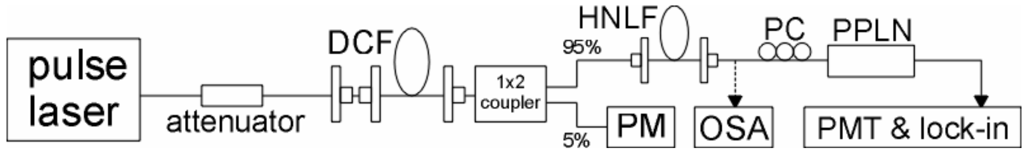

Fig.1: Experimental setup. DCF: dispersion compensating fiber, HNLF: highly nonlinear fiber, PC: polarization controller, PPLN: periodically poled lithium niobate, PMT: photomultiplier tube, OSA: optical spectrum analyzer, PM: power meter.

Fig.2 shows the fundamental power spectra measured after the HNLF at coupled powers of 302 μW (solid) and 476 μW (dash-dot), respectively. Compared with the spectrum before the HNLF (dashed), SPM-induced spectral broadening is evident at these power levels. Fig. 3 shows the narrowband SHG yield $\langle P_{2\omega}\rangle$ versus the fundamental power coupled into the HNLF. For powers much less than ~100 μW, the SPM effect is weak and $\langle P_{2\omega}\rangle$ roughly grows with the square of the fundamental power (the linear fit for the first three points on a log-log scale has a slope of 1.71). At higher input powers, SPM in the 15-m-long HNLF greatly distorts the temporal phase profile and reduces $\langle P_{2\omega}\rangle$. Compared with the typical square-dependence between the SH and fundamental powers, our data show the strong effect of temporal phase on $\langle P_{2\omega}\rangle$. We also found that $\langle P_{2\omega}\rangle$ decreases with SPM monotonically except for some particular cases of very strong chirp (~450 μW in Fig. 3), where the interplay between $I(t)$ and $\phi(t)$ could increase $\langle P_{2\omega}\rangle$ when the induced $\phi(t)$ scales up.

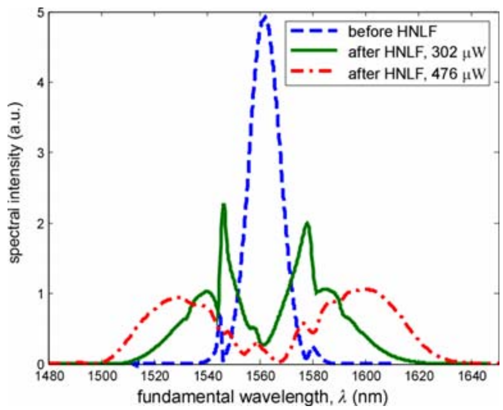

Fig. 2. Power spectra measured before (dashed) and after (solid, dash-dot) the HNLF.

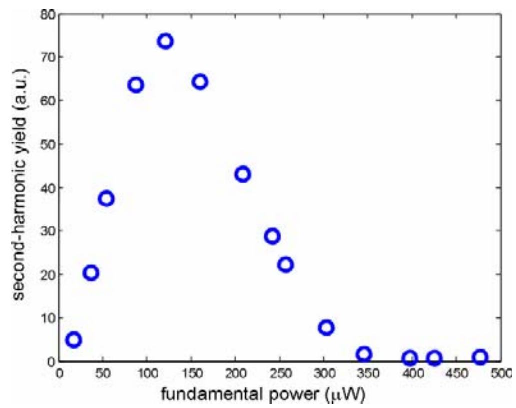

Fig. 3. Narrowband SHG yield versus the fundamental power coupled into the HNLF.

4. Conclusions and acknowledgements

In conclusion, we have experimentally demonstrated that the narrowband SHG yield is highly sensitive to the SPM-induced temporal chirp. Complete extinction of SHG yield can be realized by introducing a $\pi/2$-phase jump at the center of a temporally symmetric pulse, which is useful in ultrafast coherent communications. We acknowledge Dr. J. -L. Peng for supporting the highly nonlinear fiber. This material is based upon work supported by National Science Council of Taiwan under grant NSC 98-2221-E-007-031, and U.S. Air Force Office of Scientific Research under grant FA9550-09-1-0233.

5. References

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