Measurement of phase-matching spectral phase by nonlinear spectral interferometry

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Abstract：We experimentally measured the phase-matching spectral phase of chirped quasi-phase matched gratings for the first time (to the best of our knowledge), which is essential in determining the nonlinear signal shape and domain distributions.

1. Introduction

Quasi-phase matching (QPM) has been extensively used in wavelength conversion processes owing to the advantages of using noncritical propagation geometries, accessing to larger nonlinear susceptibility tensor components, and the capability of engineering the amplitude and phase of the phase-matching responses. For example, chirped QPM gratings have been applied to femtosecond pulse measurements [1,2]. Nonlinear conversion at discrete wavelengths with arbitrary relative efficiencies can be achieved by optimized nonperiodic QPM gratings [3], which is useful in multi-channel packet routing in optical telecommunications [4]. Phase-matching spectral phase modulation, however, plays a pivotal role in the temporal shaping of ultrafast nonlinear signals. For example, sub-6-fs blue pulses at 405 nm [5] were produced by passing strongly chirped fundamental pulses through chirped QPM gratings for second-harmonic generation (SHG). Aperiodic QPM gratings optimized by simulated annealing were used to generate second-harmonic pulses with prespecified intensity and phase profiles [6]. In these applications, experimental diagnosis for the phase-matching spectral phases of the aperiodic QPM gratings is essential to ensure the fidelity of the generated pulse shapes. We proposed and experimentally demonstrated a new scheme to directly retrieve the phase-matching spectral phase by measuring a second-harmonic interferogram. To the best of our knowledge, this is the first experimentally proven method for phase-matching spectral phase measurement.

2. Theory

Spectral interferometry (SI) is a linear technique to measure the spectral phase difference between two optical signals [7]. Let $A_s(\omega)$ and $A_r(\omega)$ represent the spectral envelopes of the signal and reference pulses of the same carrier angular frequency ω_0, respectively. If the two pulses are separated by a relative time delay τ, the resulting power spectrum (interferogram) is formulated by:

$$S(\omega) = |A_s(\omega)|^2 + |A_r(\omega)|^2 + 2|A_s(\omega)A_r(\omega)|\cos[\tau\omega + \psi_s(\omega) - \psi_r(\omega) + \omega_0\tau], \quad (1)$$

where $A_i(\omega)=|A_i(\omega)|\exp[j\psi_i(\omega)]$ ($i=s, r$). In the nonlinear SI, the signal and reference pulses come from SHG of a fundamental pulse passing through the test QPM grating and the reference thin nonlinear crystal with phase-matching responses $H_i(\Omega)=|H_i(\Omega)|\exp[j\psi_{H_i}(\Omega)]$ ($i=s, r$), respectively (Ω denotes the frequency detuning from $2\omega_0$). The fringe density of the second-harmonic interferogram $S(\Omega)$ depends on $\Delta\psi(\Omega)=\psi_{H_s}(\Omega)-\psi_{H_r}(\Omega)$, which will be equal to the desired $\psi_{H_s}(\Omega)$ if the reference crystal is sufficiently thin such that $\psi_{H_r}(\Omega)\approx 0$ within the frequency range of interest. Note that nonlinear SI will work as long as the main lobe of $|H_r(\Omega)|$ is broader than $|H_s(\Omega)|$, relaxing the restriction about the thickness of the reference crystals.

3. Experiments

Fig. 1 shows the experimental setup of nonlinear SI. A passively mode-locked fiber laser produced 50 MHz, 300 fs, 1.4 mW pulses at 1560 nm. The -10 dB bandwidth of the fundamental spectrum was broadened from 24 nm to 79 nm (spanning from 1527 nm to 1606 nm) by passing the pulses through a section of 15-m-long highly nonlinear fiber. The p-wave and s-wave components were separated by a polarization beamsplitter, focused into a 1-mm-thick type 1 BBO crystal and a 49.5-mm-long MgO-doped $LiNbO_3$ crystal with different types of QPM gratings (HC Photonics) to generate the second-harmonic reference and signal pulses, respectively.

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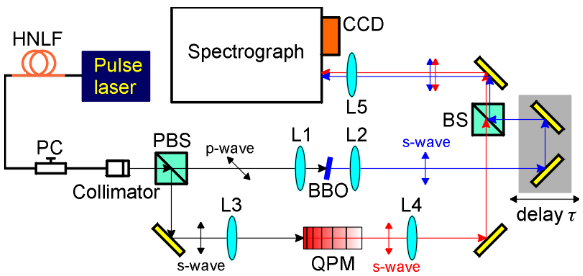

Fig. 1. Experimental setup. HNLF: Highly nonlinear fiber. PC: Polarization controller. PBS: Polarization beamsplitter. L#: Lens. BS: Beamsplitter.

The poling period distributions $\Lambda(z)$ are linear (QPM-1) and quadratic (QPM-2) functions between 19.9 μm and 20.4 μm, corresponding to fundamental phase-matching wavelengths between 1566 nm and 1586 nm (783-793 nm in second-harmonic band), respectively. The broad input spectral width and the thin BBO crystal (phase-matching wavelengths beyond 1520-1630 nm) ensure that the interference occurs over the entire phase-matching spectrum $H_s(\Omega)$ of each QPM grating. The two s-polarized second-harmonic beams were combined by a beamsplitter, focused into a spectrograph (iHR550, Jobin Yvon), and recorded by a CCD array to get the interferogram $S(\Omega)$.

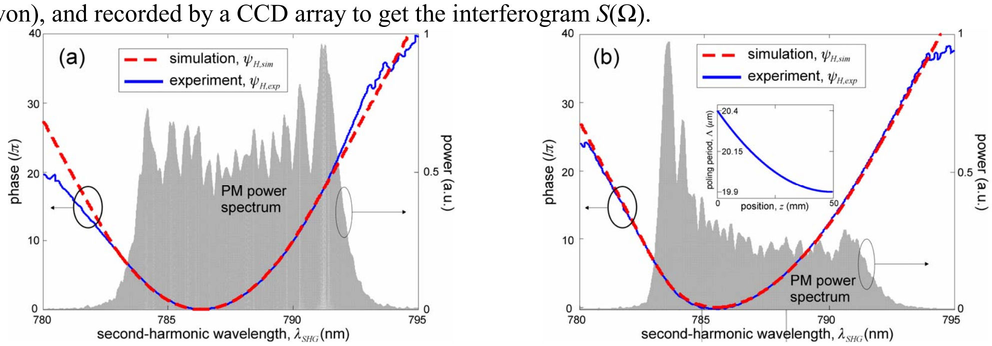

Fig. 2. Experimentally measured phase-matching power spectra (shaded), and phase-matching spectral phases obtained by simulation (dashed) and experiment (solid) of (a) QPM-1, and (b) QPM-2, respectively. Inset of (b) shows the quadratic poling period function of QPM-2.

As shown in Fig. 2, the experimentally measured phase-matching spectral phases $\psi_{H,\mathrm{exp}}$ (solid) of both QPM gratings are in good agreement with the simulated counterparts $\psi_{H,\mathrm{sim}}$ (dashed) over the spectral range where the phase-matching power spectra $I_H(\Omega)=|H_s(\Omega)|^2$ (shaded) are non-negligible. The accuracy of the measurements can be quantitatively estimated by the rms phase error:

$$\varepsilon_{rms} \equiv \sqrt{\sum_{i=1}^{N} \left[\psi_{H,\mathrm{exp}}(\lambda_i) - \psi_{H,\mathrm{sim}}(\lambda_i)\right]^2 \cdot \tilde{I}_H(\lambda_i)}\ ,$$

where $\tilde{I}_H$ is the normalized phase-matching power spectrum ($\sum_{i=1}^{N} \tilde{I}_H(\lambda_i) = 1$), and λ_i (i =1-N) indicates the sampled wavelength. The corresponding minimum value, mean value, and standard deviation of ε_{rms} in 10 times measurements of QPM-1 (QPM-2) are 0.311π, 0.319π, 0.006π (0.206π, 0.222π, 0.032π), respectively, proving the integrity of our method.

4. Conclusions

We experimentally demonstrated a new scheme to directly retrieve the phase-matching spectral phase by measuring a second-harmonic interferogram. The nonlinear SI is fast, nondestructive, applicable to arbitrary QPM gratings, and has high sensitivity and accuracy. In combination with the phase-matching spectral intensity, it can be used to completely reconstruct the domain distributions.

5. Reference

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