Amplitude modulation and apodization of quasi-phase-matched interactions

Jie Huang, X. P. Xie, Carsten Langrock, R. V. Roussev, D. S. Hum, and M. M. Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305

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We propose several techniques to modulate the local amplitude of quasi-phase-matched (QPM) interactions in periodically poled lithium niobate waveguides and demonstrate apodization by using each of these techniques. When the hard edges are removed in the spatial profile of the nonlinear coupling, the sidelobes of the frequency tuning curves are suppressed by 13 dB or more, compared with a uniform grating, consistent with theoretical predictions. The sidelobe-suppressed gratings are useful for frequency conversion devices in optical communication systems to minimize interchannel cross talk, while the amplitude modulation techniques in general have potential uses in applications that require altering the tuning curve shapes. © 2006 Optical Society of America

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Optical frequency mixers based on quasi-phase-matched (QPM) gratings in periodically poled lithium niobate (PPLN) waveguides with very high nonlinear efficiency have been demonstrated.[1] Uniform QPM gratings have made many important all-optical signal-processing functions possible, including wavelength conversion,[2] dispersion compensation by spectral inversion,[3] 160 Gbit/s optical time-division multiplexing,[4] and all-optical sampling.[5] Various quasi-phase-matching engineering techniques have been developed to expand their applications, e.g., chirped gratings for femtosecond pulse compression and shaping,[6] transversely patterned gratings for nonlinear physical optics,[7] multichannel devices based on grating phase modulation,[8,9] and quasi-group-velocity matching to increase the bandwidth–efficiency product.[10]

With all of the above developments, a convenient technique to modulate the amplitude of QPM interactions is not yet available. Amplitude modulation is difficult for a device based on ferroelectric domain reversal, because unlike electronic filters to which virtually any analog window function can be applied, a QPM grating is essentially a digitized structure with a local nonlinear coefficient that is either plus or minus that of the material. Nevertheless, amplitude modulation of QPM gratings is important, because the frequency response (tuning curve) of a nonlinear device is proportional to the Fourier transform of its spatial profile of nonlinear coupling, and it is useful to be able to alter the shape of a tuning curve in certain applications.

The tuning curve shape of a frequency conversion device is important in optical communications. In a nonlinear mixing process, only the channel whose wavelength corresponds to the center peak of the tuning curve should undergo frequency conversion. However, those channels whose wavelengths correspond to the side peaks will also be converted and thus introduce cross talk in many applications, including optical time-division multiplexing and wavelength-division multiplexing. The intrinsic sinc-sqaure tuning curve of a uniform grating is typically unsatisfactory in that the ratio between its first side peak and main peak is only −13 dB, and its sidelobes decay only quadratically with detuning. However, cross talk below −30 dB is often required for communication systems. To achieve this goal, a sidelobe-free tuning curve is most desirable.

Fourier transform analysis shows that the tuning curve sidelobes can be suppressed if the QPM interaction is apodized, i.e., if the hard edges of the spatial profile of nonlinear coupling are removed. In this Letter we propose and compare different techniques for amplitude modulation of QPM interactions in PPLN waveguides and report experimental demonstration of sidelobe-suppressed tuning curves made available by use of those techniques.

It is in principle possible to modulate the effective nonlinear coefficient d_{eff} by locally changing the duty cycle D of a grating period, since $d_{\mathrm{eff}} \propto \sin(\pi D)$.[11] In practice, however, an adequate modulation with d_{eff}'s being 10% that of a 50%-duty-cycle grating would require a duty cycle of roughly 3%, which corresponds to a domain length of 0.5 μm for a C-band PPLN device, currently not available.

The nature of waveguide optics makes possible other techniques to modulate the local amplitude of the nonlinear coupling. Under the undepleted pump and no-loss limit, the generated second-harmonic (SH) output power can be written as

$$P_{2\omega}(L) \propto \left| \int_0^L \kappa(z) \exp\{-j[\phi_2(z) - 2\phi_1(z)]\} \mathrm{d}z \right|^2, \quad (1)$$

where $\kappa(z)$ is the local amplitude of the nonlinear coupling, defined as

$$\kappa(z) = \nu(z) P_{\omega}(z), \quad (2)$$

and $\nu(z)$ is the overlap integral,

$$\nu(z) = \int\int d(x,y,z) \bar{E}_{\omega}^2(x,y) \bar{E}_{2\omega}^*(x,y) \mathrm{d}x \mathrm{d}y. \quad (3)$$

In the above relations P_ω, $P_{2\omega}$ and ϕ_1, ϕ_2 are the powers and phases of the first harmonic (FH) and SH waves, respectively, $\bar{E}_\omega$ and $\bar{E}_{2\omega}$ are the spatial distributions of the FH and SH modal fields normalized so

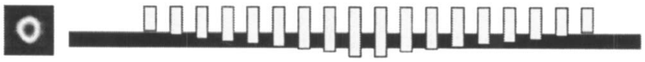

Fig. 1. Schematic of a mode-overlap-control device.

Fig. 2. The double-coupler structure modulates the amplitude of the nonlinear coupling and hence the QPM interactions in a waveguide, although the grating itself is uniform.

that their integral over space is unity, and d is the spatial distribution of the nonlinear coefficient. $\bar{E}_{\omega}$ and $\bar{E}_{2\omega}$ of a waveguide are both calculable from the refractive index distribution of the waveguide and measurable in experiments. The function $d(x,y,z)$ can be defined in lithography by positioning the gratings. With the gratings patterned into and out of the waveguide, the overlap of the waveguide mode with the nonlinearity of the periodically poled material is modulated (Fig. 1). This mode-overlap-control approach bears similarity to the previously demonstrated odd-mode quasi-phase-matching by angled and staggered gratings[12] in that they both manipulate the overlap integral by changing $d(x,y,z)$. With this mode-overlap-control method, virtually any spatial profile of $\nu(z)$ can be obtained by a lithographically defined poling pattern.

An alternative to the above scheme, which modulates $\nu(z)$, is to modulate $P_{\omega}(z)$ in Eq. (2). This can be realized by integrating two directional couplers with a QPM grating, as shown in Fig. 2. The FH wave is coupled into and out of the QPM grating by the two couplers. With a constant-gap constant-waveguide-width coupler, $P_{\omega}(z)$ in the QPM grating varies with a raised cosine curve. This structure, although incorporating a uniform grating, will have a frequency response identical to that of a QPM grating with $d_{\mathrm{eff}}(z) \propto 1-\cos(\pi z/l_c)$, where l_c is the length of one coupler.

A third scheme uses a deleted-reversal pattern to directly modulate the amplitude of the QPM grating and match the spatial profile of nonlinearity to a target function (Fig. 3). The reversals are deleted (meaning no ferroelectric domain reversal in some grating periods) in such a way that the integrated nonlinear coefficient of the grating over any two end points equals that of the target function. The analog target function is thus converted to a digitized QPM grating. Similar to the mode-overlap-control method, the target function can be freely chosen here.

To demonstrate the above amplitude-modulation schemes, we fabricated devices on a 25 mm long $LiNbO_3$ chip. The reverse-proton-exchange waveguides[1] have 3.2 μm wide mode filters at the input section, followed by tapers to increase the waveguide width to the 7.5 μm noncritical width for quasi phase matching. Each directional coupler is 1.7-mm long and consists of two 7.5 μm wide parallel waveguides separated by 2.5 μm. It was designed to couple out more than 99% of the FH but have little coupling at the SH (typically below 1%). The QPM period is 16.10 μm, and the grating lengths l_g are 5.64 mm for mode-overlap-control and deleted-reversal devices, and 3.4 mm for the double-coupler device.

Figure 4 shows measured SHG tuning curves of QPM gratings using each of the three apodization methods, together with the tuning curve of a uniform grating for comparison. We used three different target functions, $\mathrm{sinc}(2\pi z/l_g)$, $\cos^2(\pi z/l_g)$, and $\exp[-(3.3z/l_g)^2]$, with $z=0$ being the center of the grating, for the mode-overlap-control, double-coupler, and deleted-reversal devices, respectively. In all three apodized cases, the apodization has a clear effect on sidelobe amplitudes. The sidelobes are suppressed to 13–17 dB below the −13 dB characteristic of the first sidelobe of a sinc-square pattern. The contrast approaches the goal of −30 dB when the detuning is equal to or greater than the third zero on the sinc-square curve of a uniform grating of the same length. Consistent with Fourier transform analysis, apodization has the effects of reducing peak efficiency (not shown) and broadening the main lobe. If these effects are of concern, apodizing a grating twice as long as the uniform one will fully compensate for both effects. Figure 5 shows the tuning curves of three gratings, all with 350 QPM periods and a raised cosine functional form in the apodized portion but different lengths of uniform gratings in the middle. They illustrate that the longer the uniform grating is, the narrower the bandwidth of the main lobe, but the higher the sidelobes. The two effects

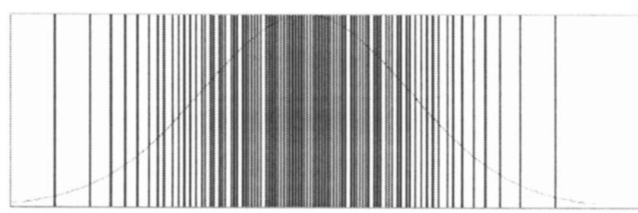

Fig. 3. Deleted-reversal grating and the target function of $d_{\mathrm{eff}}(z)$.

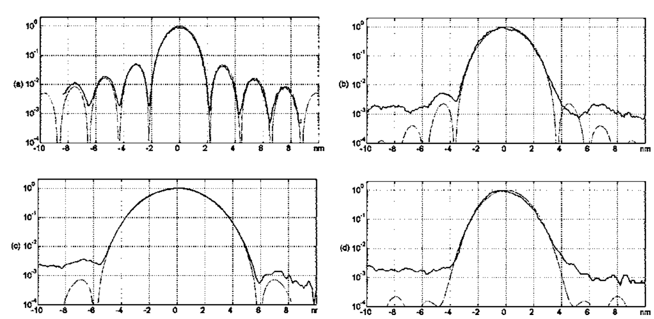

Fig. 4. Experimental (solid) and theoretical (dashed) SHG tuning curves of (a) a uniform grating and three apodized gratings, using (b) mode-overlap control, (c) the double-coupler scheme, and (d) the deleted-reversal method, respectively. In each case the side-lobes have been clearly suppressed with respect to those of the uniform grating. The grating in (c) is 3.4 mm long, i.e., twice the coupling length, so its tuning curve is wider than that of the 5.64-mm-long gratings in the other three graphs.

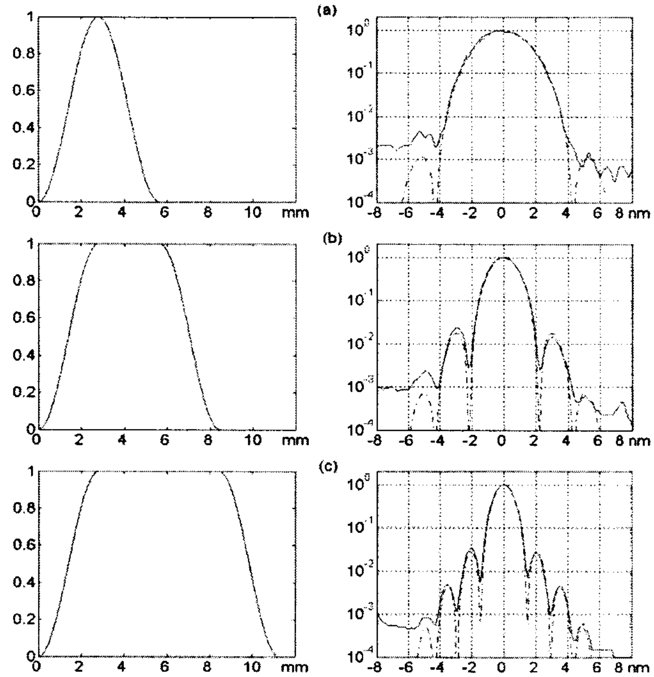

Fig. 5. $\kappa(z)$ profiles (left) and the corresponding tuning curves (right) of three apodized gratings, compared with theoretical calculations (dashed curves).

nearly cancel, so that the 30 dB bandwidth (defined as the greatest detuning that reaches above −30 dB in the theoretical curve) is relatively constant for the three cases. The measured tuning curves agree well with theoretical calculations in all but one aspect: the measured tails reach a floor whose level is roughly $1/N$, where N is the total number of grating periods. This floor exists for uniform gratings as well and is due to random variation in domain center positions or waveguide inhomogeneities, of which further study is being done.

Comparing the three amplitude-modulation techniques, we note that the deleted-reversal devices are the easiest to fabricate and are not sensitive to alignment errors between gratings and waveguides as are the mode-overlap-control devices or to inaccurate coupler lengths as are the double-coupler devices. Moreover, deleted-reversal devices can be used in bulk devices with modifications that take into account the power density change due to beam diffraction. However, they may not be suitable for applications involving sub-hundred-femtosecond pulses, as the walk-off length between FH and SH waves becomes so short that the digitization effects could be significant. The double-coupler scheme has the advantage of separating the FH and SH light automatically. But unlike the other two methods, the simple design described here has a fixed raised cosine $\kappa(z)$. However, with more complicated designs, varying the distance between the two waveguides of the coupler for instance, it could also accommodate other target $\kappa(z)$ profiles.

In summary, we have proposed three techniques to modulate the amplitude of the QPM interactions in PPLN waveguides and demonstrated apodization of QPM interactions and tuning curve sidelobe suppression by using those techniques. In a wider context, these amplitude-modulation techniques are not limited to apodization but can be used for many other applications that require the alteration of tuning curve shapes.

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