Quasi-group-velocity matching using integrated-optic structures

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We propose a device to compensate for group-velocity mismatch (GVM) effects that limit the efficiency–bandwidth product in nonlinear frequency-mixing devices. Integrated wavelength-dependent delay lines are introduced periodically in a waveguide containing a series of quasi-phase-matching (QPM) gratings. Appropriate choice of the time delays can compensate for GVM. We have demonstrated a two-stage device in a periodically poled lithium niobate waveguide. Two approximately 150-fs-long pulses generated 6 ps apart by second-harmonic generation in two QPM gratings were resynchronized by a fixed delay line, and their relative phase was fine controlled by temperature tuning. This technique, which can be iterated to more than two segments, permits optical frequency mixers with a higher efficiency–bandwidth product than would be possible in a single grating short enough to avoid GVM effects.

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Optical frequency (OF) mixers based on periodically poled lithium niobate (PPLN) waveguides have been used to demonstrate many important all-optical signal-processing functions for communications systems, including wavelength conversion,[1–3] dispersion compensation by spectral inversion,[4] 160-Gbit/s optical time-division multiplexing,[5] and all-optical sampling.[6,7] Although OF mixers are among the fastest optical signal processing devices available today, for devices involving modulation of the pump wave (such as the latter two listed above) they have speed limits set by group-velocity mismatch (GVM) between the interacting first-harmonic (FH) and second-harmonic (SH) waves.[8] With a cw pump, standard OF mixers operated at a FH wavelength of 1550 nm have over 1 THz of conversion bandwidth. However, in pump modulation devices the SH pump consists of short optical pulses. The SH and FH pulses propagate at different speeds through the interacting section. At high enough speeds, cross talk can occur when the envelopes of the two pulses walk off each other into neighboring time slots. Here we propose and demonstrate a method to avoid these limitations.

The characteristic length over which FH and SH pulses walk off each other is called the group-velocity walk-off length, $L_{\mathrm{gv}} = \tau_1/|\delta v|$, where τ_1 is the FH pulse width and $\delta v = 1/u_1 - 1/u_2$ is the GVM parameter[9]; u_1 and u_2 are the group velocities of the FH and SH pulse envelopes, respectively. GVM limits the maximum interaction length for short pulses, resulting in reduced efficiency, which is proportional to the square of the interaction length in SH generation or to the fourth power of that length in cascaded processes.[10] For 3-ps pulses, typical of 160-Gbit/s systems, the maximum interaction length is $\sim$1 cm in a PPLN OF mixer, only 1/5 that of a standard device. It is thus very useful to have some group-velocity-matched structure so that the interaction length is no longer limited to one walk-off length, thereby obviating the bandwidth–efficiency trade-off.

A quasi-group-velocity matching device is shown schematically in Fig. 1. After a first quasi-phase-matching (QPM) grating, the FH pulse is selectively coupled into a parallel waveguide, delayed by a small-radius bend, and then coupled back into the original waveguide, now retimed to overlap the SH pulse, generating a second SH pulse synchronized to the first. A single quasi-group-velocity matching stage doubles the effective interaction length for the pulses. The structure can be iterated to obtain even higher efficiency without sacrificing bandwidth, until pulse broadening as a result of group-velocity dispersion becomes significant when the total device length is long enough.

Correct operation of the device requires not only that the envelopes of the SH pulses be synchronized but also that the carrier phase of the pulses be correct. When the SH pulses generated in the two sections are in phase, they interfere constructively, and energy flows from FH to SH in the second QPM grating. Meeting this condition requires precise positioning of the QPM gratings. Given the difficulty of calculating the absolute phase shift through the directional couplers and bends, we used temperature tuning to meet this requirement. The relative phase of the pulses changes with temperature, because of the change in the

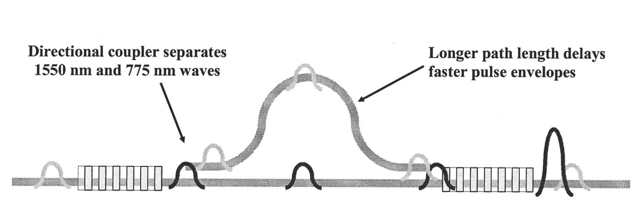

Fig. 1. Schematic of a quasi-group-velocity matching device. Faster fundamental frequency pulses (gray) are delayed by a bent waveguide to resynchronize with the slower SH pulses (black) in the second conversion section.

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effective refractive index with temperature and the thermal expansion of the crystal:

$$\phi(\Delta T) = k_{2\omega}\left(n_2 + \frac{\mathrm{d}n_2}{\mathrm{d}T}\,\Delta T\right)L_{\mathrm{str}}(1 + \alpha_{\mathrm{LN}}\Delta T) - 2k_{\omega}\left(n_1 + \frac{\mathrm{d}n_1}{\mathrm{d}T}\,\Delta T\right)L_{\mathrm{bent}}(1 + \alpha_{\mathrm{LN}}\Delta T), \quad (1)$$

where ϕ is the relative phase of the two SH pulses; ΔT is the temperature change; k_{ω} and $k_{2\omega}$ are the FH and SH wave vectors in vacuum, respectively; n_1 and n_2 are the effective refractive indices at FH and SH wavelengths, respectively; L_{str} and L_{bent}, are the lengths of straight and bent waveguides, respectively; and α_{LN} is the thermal-expansion coefficient of lithium niobate. As an estimate, for a delay section of 15 mm, one needs a temperature change of approximately 8 °C to tune the phase by 2π. Therefore, given any initial phase of the two SH pulses, a temperature tuning of ± 4 °C is enough to obtain optimum operation.

To demonstrate this quasi-group-velocity matching scheme, we fabricated our devices on a z-cut lithium niobate chip. The waveguides were proton exchanged to an initial depth of 0.7 μm and annealed for 26 h at 325 °C. There are 4-μm-wide mode filters at the input and output, and the straight waveguides and bends are both 8 μm wide. The bends have a radius of 4 mm, for which the additional loss as a result of bending is negligible. The length of the bent sections ranges from 10.18 to 13.61 mm, exceeding the length of the straight sections by 0.36 to 0.80 mm, providing a different time delay in each device. The directional coupler at each end of the bend is 1.7 mm long and consists of two 8-μm-wide parallel waveguides separated by 3 μm. It is designed to couple out over 99% of the FH but have little coupling at the SH (typically below 1%). Two sections of QPM gratings predefined by electric-field poling[11] are adjacent to each directional coupler. They are 0.269 and 0.538 mm long, with a QPM period of 15 μm. This choice of grating lengths differs from the nominal design but allows for convenient testing by generating two clearly distinguishable pulses (with different pulse energies). A reference device lacking the delay section but otherwise identical to the full devices was fabricated adjacent to each set for comparison purposes. The GVM parameter that we used in designing all devices, 0.36 ps/mm, was obtained in other experiments.[12]

When testing the device, we used 150-fs pulses at a FH wavelength of 1545 nm generated at an 82-MHz repetition rate by a femtosecond optical parametric oscillator (Spectra-Physics Opal) pumped by a mode-locked Ti:sapphire laser. The FH pulse was split into pump and reference beams. The pump beam, with an average power of 0.5 mW, was coupled into the PPLN device to generate the SH signals. The reference beam was passed through a delay line and then cross correlated with the SH signals through two-photon processes in a GaAsP photodiode. The device was heated to 75 °C to suppress photorefractive effects.

Figure 2 shows the cross-correlation traces of a reference device, together with four GVM compensation devices. The reference device [Fig. 2(a)] has no GVM compensation, and two SH pulses are generated 6 ps apart. The energy in the first pulse is roughly four times that of the second, as expected for our design, in which one grating is 0.7 walk-off lengths long and the other is twice that length.[9] The pulse widths are measured to be 150 and 180 fs after deconvolution of the 150-fs reference pulse, consistent with calculations[9] using the grating lengths and the FH pulse width. The first pulse becomes slightly longer than the second because it propagates a longer distance and hence undergoes more group-velocity dispersion at the SH wavelength. In the other devices [Figs. 2(b)–2(d)], GVM is partially compensated for, and the two pulses move closer as the added delay increases toward 6 ps. Finally in the device in Fig. 2(e), the two pulses are well synchronized, as we expect. The offset of the two envelopes after compensation is measured to be 80 fs. This was determined by the best fit of trace (e) to two pulses with various amounts of offset.

Figure 3 shows the temperature-tuning results of the device shown in Fig. 2(e). In an 8 °C cycle the two overlapping pulses go between in and out of phase, and hence the output optical power assumes maximum and minimum alternately. This temperature tuning is small enough compared with the approximately 250 °C temperature-tuning bandwidth of the QPM gratings that we used. Furthermore, over the 8 °C change in temperature, the overlap of the pulse envelopes is not affected. This is critical to the success of the scheme: the necessary temperature change to obtain the correct phase is not so large as to move the envelope of one pulse off that of the other, neither is it so small as to impose a strict temperature stability requirement for a stable output. In this device the ratio of maximum to minimum output power over the

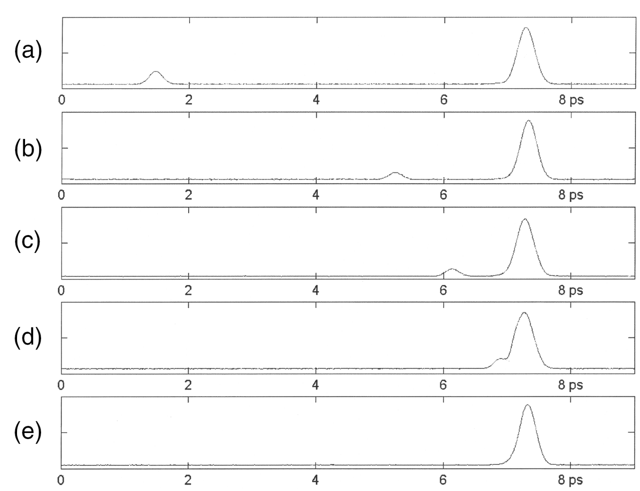

Fig. 2. Cross-correlation traces of (a) a reference device and (b)–(e) four GVM compensation devices. The two pulses move closer as the added delay increases. The envelopes finally overlap well in device (e).

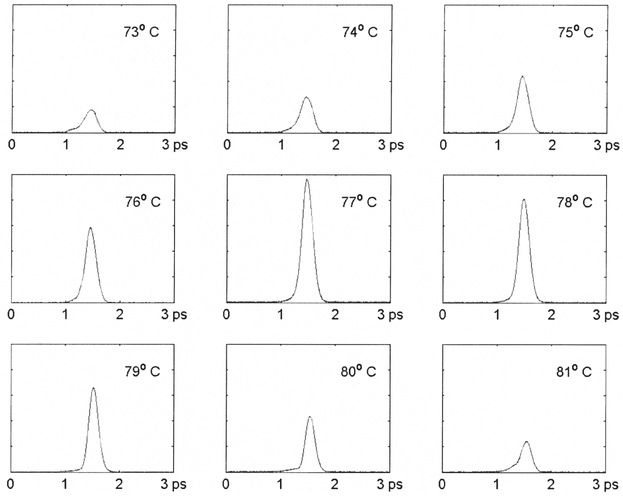

Fig. 3. Temperature tuning of device (e) in Fig. 2. The relative phase changes by 2π over 8 °C. The precision of temperature control is ± 0.1 °C.

range of relative phases is approximately 7:1, implying two pulses with a peak power ratio of 5:1.

In summary, we have demonstrated a design for a quasi-group-velocity matching device in an integrated PPLN waveguide structure. The proof-of-principle device has the expected pulse widths, GVM compensation, and temperature-tuning behavior. It extends the interaction length beyond the limit of one walk-off length of the 150-fs input pulses. In future work multisection devices, fundamental limitations imposed on them by group-velocity dispersion, and practical limitations due to finite bend radii will be investigated.

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