Second-harmonic generation in waveguides induced by photorefractive spatial solitons

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Received March 24, 1999

We demonstrate experimentally second-harmonic generation in waveguides induced by photorefractive solitons and show that the conversion efficiency is improved considerably. These induced waveguides are flexible and can be generated in any crystalline direction that allows soliton formation, and thus offer broad tunability (by rotation of the crystal), which cannot exist in fabricated waveguides. © 1999 Optical Society of America

OCIS codes: 190.5530, 190.2620, 190.5330, 230.7370, 260.1180.

Photorefractive spatial solitons¹ induce waveguides that offer potential applications, some of which are truly unique^{2,3}: reconfigurable near-field optical interconnects, three-dimensional optical circuitry,⁴ directional coupling,⁵ beam steering, and frequency conversion.^{2,3} The properties that make photorefractive soliton-induced waveguides so interesting are dimensionality, wavelength sensitivity, and fixability. Dimensionality means that solitons self-trap in (2 + 1)D and induce two-dimensional waveguides.⁶ Wavelength sensitivity results from the fact that photorefractivity is driven by charge carriers that are photoexcited from impurities, so the photoexcitation cross section varies with wavelength. Thus one can generate a photorefractive soliton at a highly sensitive wavelength and guide in its induced waveguide a probe beam at a nonphotosensitive wavelength. In this manner a very weak soliton can guide and steer an intense beam.⁷ Fixability is the ability to impress the soliton-induced waveguides into the crystalline lattice and create fixed waveguides. Such waveguides can be written, erased, and rewritten in a different site or direction by virtue of the interplay of temperature, electric field, and the hysteresis curve.⁴

The most unique application of waveguides induced by photorefractive solitons is nonlinear frequency conversion (first proposed in Ref. 2). Since the conversion efficiency of second-harmonic generation (SHG) and other $\chi^{(2)}$ parametric processes scales with the intensity of the pump beam, it is desirable to confine the interacting beams in a waveguide. There, phase matching occurs among propagation constants of the interacting guided modes, rather than wave vectors in a bulk. Phase matching is obtained by use of birefringence or periodic poling. In a fabricated waveguide, little SHG wavelength tuning exists,⁸ because the structure is fixed. Tuning techniques rely on angle and temperature,⁸ with some extended tuning in structures with several periods of poling⁹ that are laterally parallel to one another. Obviously, it is highly desirable to have waveguides in which phase matching or the propagation constants are tunable.

Waveguides induced by photorefractive solitons offer just that: a large degree of tuning of all waveguide parameters, along with the fact that most photorefractives have large $\chi^{(2)}$. This tunability to-

gether with the dimensionality, wavelength sensitivity, and fixability, makes nonlinear frequency conversion in waveguides induced by photorefractive solitons attractive. A waveguide can be induced by a μ W soliton and guide in it two (or three) intense beams, all of longer wavelengths, interacting through $\chi^{(2)}$. Phase matching can be achieved with birefringence or by means of periodic poling. One can achieve wavelength tunability by simply rotating the crystal and launching a soliton at a new direction.¹⁰ Essentially, the tuning range should be close to that in bulk. In fabricated waveguides such tunability is nonexistent because the directions of propagation are dictated by the fabricated structure, which allows no flexibility. Finally, the propagation constants of the guided modes in the waveguides induced by photorefractive solitons are also tunable by variation of the intensity ratio,³ allowing tuning with no mechanical movements.

Here we demonstrate SHG in waveguides induced by photorefractive screening solitons. We employ two methods: active and passive. In the active method a soliton beam guides the interacting first- and second-harmonic (SH) beams. In the passive method the SH beam forms a soliton and guides in its induced waveguide the first-harmonic beam. In both cases the conversion efficiency is significantly improved from the same experiment with diffracting beams.

Consider a Gaussian beam of the fundamental frequency launched into a nonlinear medium, with its minimum waist at the input surface, and assume that phase matching is satisfied. If this beam is propagating without diffraction, i.e., its width is equal to the input width, then under the nondepleted pump approximation the SH output power is proportional to the crystal length squared (L^2). However, in a homogeneous medium the beam diffracts, and the intensity decreases with propagation. Thus the SH output power is proportional to $z_0^2 \ln^2\{L/z_0 + [1 + (L/z_0)^2]^{1/2}\}$, where z_0 is the Rayleigh length of the beam. Furthermore, as the beam diffracts, its transverse phase is not uniform, and phase matching is satisfied only in parts of the beam (typically in a ring). With deteriorated phase matching the SH output power is proportional to $z_0^2 \arctan^2(L/z_0)$. Figure 1a provides a comparison among these cases, showing the SH power as a function of normalized propagation distance, L/z_0 , with beam

width (and thus z_0) fixed and L varying. Clearly it is advantageous to have SHG with nondiffracting beams. The conversion efficiency of SHG is also improved if both the first-harmonic and the SH beams are focused to tiny spots. However, the more focused the beam is, the faster it diffracts, and again the conversion is reduced because the intensity decreases and because phase matching is not satisfied across the entire beam. As a result, in a bulk crystal there is an optimum beam size for SHG given the crystal length, which occurs for $L = z_0$. The SH output power decreases if the beam is smaller than the optimum size. This is shown by curve C of Fig. 1b, where L is fixed and the beam width (and thus z_0) varies. If SHG occurs in a waveguide, the beam remains narrow and phase matching does not deteriorate even for tightly focused beams, as shown by curve A of Fig. 1b. From Figs. 1a and 1b it is obvious that, if SHG takes place in a 2D waveguide, a large improvement in conversion efficiency is expected. The dashed lines in Figs. 1a and 1b correspond to our experiments, using a $\lambda = 982$ nm, 24- μ m FWHM Gaussian input beam in a 1-cm-long crystal. We expect an improvement factor of 7 when the beam is confined in a waveguide (or self-trapped). Further reduction in beam width will result in major improvement: An 8- μ m beam (approximately the narrowest photorefractive bright soliton ever generated) in a 1-cm-long crystal will give a 425 improvement factor.

We use a 3 mm $\times$ 10 mm $\times$ 5 mm Fe-doped KNbO₃ crystal. Using interferometry, we measure electro-optic coefficients of $r_{33} = 73$ pm/V, $r_{13} = 37$ pm/V, and $r_{23} = 7$ pm/V. KNbO₃ is phase matchable for SHG by use of birefringence, at room temperature, for (fundamental) wavelengths in the near IR. For example, if the beam propagates along the b axis, the refractive index of an a -polarized 982-nm beam is equal to that of a c -polarized 491-nm beam. Or, if the beam propagates along the a axis, phase matching occurs between b -polarized 873-nm and c -polarized 436.5-nm beams. We use the former, in which the waveguide-related electro-optic coefficient is r_{13} (in the latter the relevant coefficient is r_{23} , which is much smaller).

First we measure the SHG in the bulk KNbO₃ crystal. We launch a circular $\sim$ 982-nm a -polarized cw beam along the b axis. The input (minimum) beam width is 22 μ m $\times$ 22 μ m (FWHM), and the input power is 15 mW. At the output we use a color filter and measure the SH power. By fine tuning, we obtain phase matching at $\lambda = 982.6$ nm. After 1-cm propagation, the output power at $\lambda = 491.3$ nm is 350 nW, with a conversion efficiency of 0.15%/W.

Then we pursue the active method. The setup is similar to that in Ref. 11. We use a 488-nm c -polarized beam to generate the soliton and use the induced waveguide to guide the fundamental beam. A uniform 488-nm a -polarized beam is used as the background illumination. All beams propagate along the b axis, and the voltage is applied along the c axis. Since the SH is at a photorefractive-sensitive wavelength, it can affect the soliton. To minimize this effect we use a chopper in the path of the cw (IR) fundamental beam, making it pulsed, with an on-off ratio of 1/35, giving a pulse width much shorter

than the response time. The average power in the fundamental beam (averaged over times longer than the response time) is 9.7 nW, much smaller than that of the soliton (150 nW). In this way the SHG process does not intervene with the soliton. To make the soliton we focus the 488-nm beam to a 9 μ m $\times$ 9 μ m input (Fig. 2a). The soliton power is 150 nW, with an intensity ratio of 15. After 1-cm propagation, the beam diffracts to a 103 μ m $\times$ 118 μ m (Fig. 2b). When we apply a voltage of 2600 V, the beam self-traps into a 6 μ m $\times$ 10 μ m output (Fig. 2c). Then we launch a 982-nm a -polarized beam into this soliton-induced waveguide. At the input the IR beam is 22 μ m $\times$ 22 μ m FWHM (Fig. 2d). With no voltage on, the IR output beam is 80 μ m $\times$ 81 μ m FWHM (Fig. 2e). With 2600 V applied and after the soliton has formed, the 982-nm beam is guided by the induced waveguide and attains an output of 24 μ m $\times$ 36 μ m (Fig. 2f). The temporal response of the output SH power during soliton formation after the voltage is turned on is displayed in Fig. 3. When we just apply the voltage ($t = 0$), the SH power is very low, because at $t = 0$ the field across the crystal is uniform, and it changes the refractive indices, taking the process out of phase matching. As the space-charge field builds up, it forms the waveguide and confines the fundamental

Fig. 1. SHG in a bulk and in a waveguide: a, SH power as a function of propagation distance, with a fixed beam width (z_0 is fixed and L varies); b, SH power as a function of propagation distance, with L fixed and input beam width varying. Propagation A, in a waveguide without diffraction; B, with the beams diffracting and phase matching always satisfied; C, with the beams diffracting and phase matching deteriorating.

Fig. 2. Experimental results with the active method: (a) input 488-nm beam, (b) output 488-nm beam without voltage, (c) output 488-nm soliton, (d) input 982-nm beam, (e) output 982-nm beam without voltage; (f) output 982-nm beam guided by the soliton.

Fig. 3. Temporal response of the SH power after the voltage is turned on (squares). The dashed line is the SH power in a bulk crystal without voltage.

Fig. 4. Experimental results with the passive method: (a) input fundamental beam, (b) output fundamental beam without voltage, (c) output fundamental beam a few seconds after the voltage is on, (d) output SH beam without voltage, (e) output SH beam a few seconds after the voltage is on.

and the SH beams and reestablishes phase matching. After steady state is reached, the SH output power stays at a constant level of 2240 nW, with a conversion efficiency of 0.996%/W, 6.4 times higher than that in a bulk phase-matched crystal (dashed line in Fig. 3).

In our case the SH is at a photorefractive active wavelength, so one can use the SH beam to generate a soliton that guides both itself and the fundamental beam, without the need for an additional beam to create the soliton. This is a fully passive method in which there is only one input beam (at the fundamental frequency), and its SH creates the soliton and the induced waveguide. Experimentally, we use the cw IR beam with the chopper removed. The input IR beam is $22\text{ }\mu\text{m} \times 22\text{ }\mu\text{m}$ FWHM (Fig. 4a), and it diffracts to an output of $75\text{ }\mu\text{m} \times 78\text{ }\mu\text{m}$ (Fig. 4b). There is no SH light at the input, but through SHG a $57\text{ }\mu\text{m} \times 61\text{ }\mu\text{m}$ FWHM spot of 491-nm light emerges at the output (Fig. 4d), with a 350-nW power. Then we apply 2600 V and observe the output. As the waveguide forms, the SH output width shrinks within 2 s, and with it the output width of the fundamental beam. After a few seconds, the SH output reaches its minimum size $10\text{ }\mu\text{m} \times 13\text{ }\mu\text{m}$ (Fig. 4e), and the size of the output fundamental beam is $25\text{ }\mu\text{m} \times 38\text{ }\mu\text{m}$ (Fig. 4c). At this moment the SH output power is 810 mW, 2.3 times the SH power in a bulk crystal (Fig. 4d). After that, the output of both the SH and the fundamental beams evolves to a somewhat broader size. This

is because the intensity of the SH (which forms the soliton) varies by orders of magnitude in the propagation direction, starting from zero at the input and becoming intense at the output. Therefore the intensity ratio of this SH soliton varies during propagation, which cannot support a stationary soliton. One can compensate for this by having the background beam counterpropagate the SH at some optimized intensity.

To summarize, we have demonstrated SHG in soliton-induced waveguides, in both active and passive methods, and observed an improvement of the conversion efficiency in both. We expect much higher improvement with a longer crystal and a narrower soliton. Our minimum soliton width was limited by surface arcing of the applied field, which can be overcome by surface insulation and coatings. Frequency conversion in soliton-induced waveguides also offers a broad range of mechanical tunability by launching the soliton and the SHG in a range of phase-matchable crystalline orientations, as is done with plane waves in a bulk crystal. Such tunability is nonexistent with conventional fabricated waveguides.

This research at Princeton University was supported by the U.S. Army Research Office.

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