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SPATIAL ROUTING OF SIGNALS AT 1549 NM BY SOLITON EMISSION IN ENGINERRED NON-LINEAR WAVEGUIDES

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SUMMARY

We observed spatial addressing of light by bi-directional spatial emission of beams at a quadratically nonlinear interface in periodically poled lithium niobate waveguides. The interface consisted of the boundary between two quasi-phase-matched regions with different poling period. We show the intensity and phase-mismatch (temperature or wavelength) dependence of the phenomena.

KEYWORD

nonlinear optics, frequency conversion, optics at surface, quadratic solitons, all-optical device

INTRODUCTION

Propagation of light in the vicinity of an interface between two different nonlinear dielectrics has been widely studied in the past four decades. After the first theoretical studies published by Bloembergen and Pershan [1], many theoretical investigations were made. In this context the interaction of spatial solitons with nonlinear interfaces as a way to achieve all-optical data processing has been an important field of investigation [2-6]. However, few experimental results have been provided over the past decades [7].

In the framework of quadratically nonlinear media, the quasi-phase matching technique can be exploited to produce engineered nonlinear structures. This opens a whole range of new possibilities, that have become experimentally feasible with the progress of a reproducible fabrication of periodically poled $LiNbO_3$ (PPLN) and KTP (PPKT). Engineered quasi-phase-matched patterns showed great promise to facilitate spatial addressing by spatial solitons. Soliton self-reflection, tunneling, resonant trapping and emission in transversely varying quasi-phase-matched gratings have been predicted [8,9]. Quadratic soliton reflection at a phase-mismatched PPLN-$LiNbO_3$ interface [10] and at a nonlinear engineered PPKTP boundary [11] was recently observed. Moreover, unidirectional spatial soliton emission at a PPLN-$LiNbO_3$ interface was demonstrated [12]; in that situation, in nonlinear regime, a beam launched across a PPLN-$LiNbO_3$ interface is spatially deflected towards the PPLN region because of the repulsive potential induced by the interface.

Here we report the observation of bi-directional spatial soliton emission in a transversely engineered PPLN sample. We refer to electromagnetic nonlinear type I interaction of a fundamental wave [(FF) at 1549nm] and a second harmonic wave [(SH) at 774.5nm]. We describe the spatial dynamics of beams that propagate across a quadratically nonlinear interface in titanium-indiffused periodically poled lithium niobate slab waveguides. The interface consisted of the boundary between two quasi-phase-matched regions with different poling period. Only the FF wave was launched onto the crystal entrance. In the whole device the linear refractive index is homogeneous. In this situation, in the low-intensity linear regime the beam propagates across the interface without changing its trajectory. In the high-intensity nonlinear regime, depending on the phase-mismatch conditions (temperature or wavelength dependent) we observed bi-directional spatial soliton emission. The phenomenon of emission can be attributed to the existence of an intensity and phase-mismatch dependent potential barrier induced by the effective nonlinear interface.

INVESTIGATION

The experiments were performed in a 70mm long Ti:LiNbO$_3$ planar waveguide fabricated in a z-cut substrate by indiffusion of 70nm thick, vacuum-deposited Ti-layer at 1064°C. Two transversely interfaced micro-domain structures of Λ=16.67 μm (P1) and of Λ=16.74 μm (P2) periodicity, designed for frequency doubling at 1549nm, were generated after waveguide fabrication by electric field assisted poling. Thus, the sample exhibited a transition (the nonlinear phase-mismatched interface) between periodically poled regions (see Fig. 1).

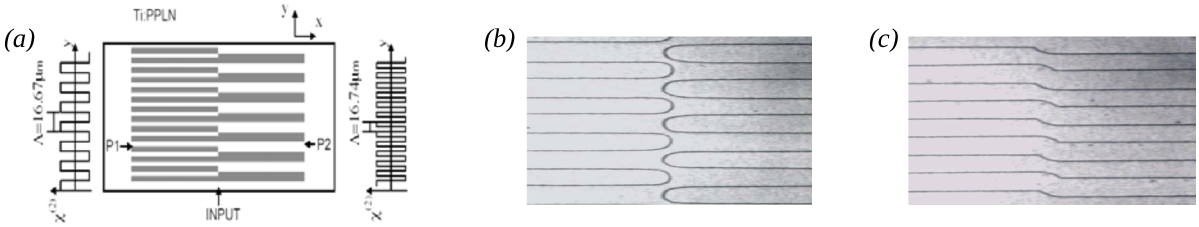

Figure 1. (a) schematic of the nonlinear engineered geometry. (b) and (c) photographs of portions of the engineered PPLN chip, showing the phase-mismatched nonlinear interface.

The sample was inserted in a temperature stabilized oven to allow operation at elevated temperatures (phase matching occurred at T=216°C in P1 and at T=198°C in P2); in this way, photorefractive effects ("optical damage") could be minimized. Moreover, temperature-tuning of the phase-matching conditions became possible.

An all-fiber laser system was used as the source of 5 ps pulses (FWHM in intensity) at 1549 nm (FF) of 1.7 nm spectral bandwidth and of a peak power of a few kilowatts at 20 MHz repetition rate. The thickness of the waveguide permitted the propagation of a single TM$_0$ mode of 4μm width at the FF; several TM modes are supported at the second harmonic (SH), but only the TM$_0$ of 3μm width is efficiently pumped by the TM$_0$ at the FF. The laser beam was shaped in a highly elliptical spot, nearly gaussian in profile, with a spot of 4μm (FWHM in intensity) along the guided dimension and with a spot of 80μm along the perpendicular direction, and was polarized parallel to the z axis of the PPLN for access to the material's largest quadratic nonlinear coefficient $\chi^{(2)}_{zzz}$=(2d$_{33}$). The spatial beam profiles were recorded by scanning a magnified image of the pattern with a photodiode. Temporal characterizations were monitored by a background free non-collinear auto-correlator. Two different filters were alternatively introduced, to select either the IR or the green output.

To model the pulse propagation, two different numerical tools have been used. A standard finite difference vectorial mode solver was employed to determine the linear propagation properties in the slab waveguide, i.e. the mode profiles, the effective index, the propagation constant, the inverse group velocity and the inverse group-velocity dispersion. In the case at hand the crystal length corresponds to 3.7 times the FF diffraction length and to 5.6 times the walk-off length between FF and SH; the dispersive terms can be neglected. The phase-mismatch temperature dependency corresponds approximately to 1.66π/°C. The phase-mismatch jump at the nonlinear interface is about 30π. Finally, using a finite difference beam propagation technique, we solved the nonlinear propagation problem.

RESULTS

We carried out experiments and numerical simulations by launching a FF input beam on the PPLN/PPLN transition and propagating parallel to the nonlinear interface, varying the phase-mismatch conditions by the temperature of the sample, and the input pulse power, keeping fixed the temporal and spatial widths of the injected FF pulse.

At first, we fixed temperature T at 204°C. In this situation, the phase-mismatch conditions in the two uniform regions are $\Delta kL_{P1}=20\pi$ and $\Delta kL_{P2}=-10\pi$. In the quasi linear regime, at low intensity, the beam broadened because of diffraction inside the crystal. By increasing the incident intensity, in nonlinear regime, we succeeded in exciting a spatial soliton and we observed its spatial emission. In Fig. 2, typical numerical and experimental results are shown. The beam experienced an intensity dependent effective spatial acceleration and consequently spatial velocity in the transverse dimension (x) towards the P1 region. The lateral velocity undergone by the self trapped beam is directly dependent and increases with the input intensity. In Fig. 3, typical numerical and experimental results are shown.

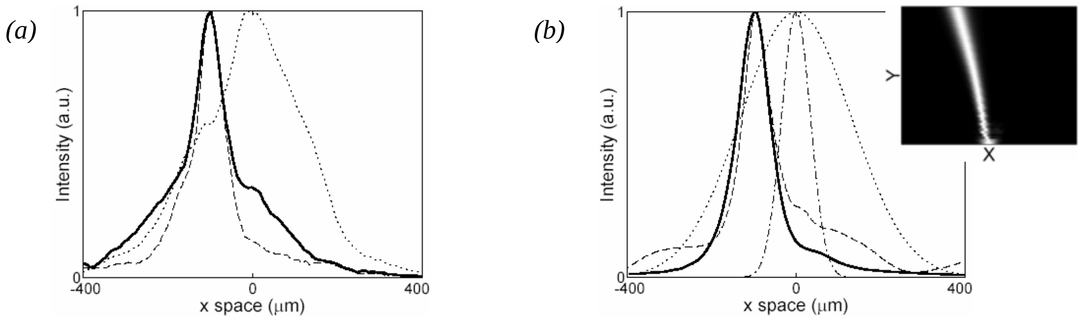

Figure 2. (a), measured and (b), calculated spatial output profiles, taken at T=204°C: FF beam in linear regime (dot curve); FF beam (solid curve) and SH beam (dash curve) at $I=160MW/cm^2$. The dash-dot curve in (b) represents the FF input profile. The inset shows the numerical FF spatial soliton evolution in the (x,y) plane, at $I=160MW/cm^2$.

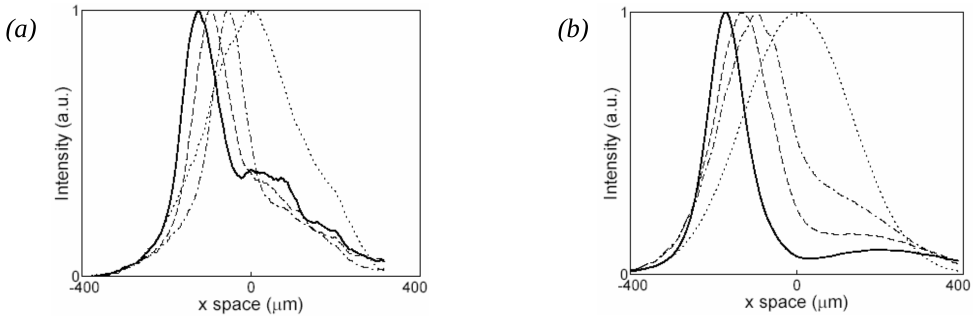

Figure 3. (a), measured and (b), calculated FF spatial output profiles, taken at T=204°C, versus input intensity: $I=1MW/cm^2$ (dot curve, quasi-linear regime); $I=70MW/cm^2$ (dash-dot); $I=120MW/cm^2$ (dash curve); $I=180MW/cm^2$ (solid curve).

In a second step, we fixed temperature T till 185°C. In this condition, the new phase-mismatch conditions are positive in both regions and are equal to: $\Delta kL_{P1}=51\pi$ and $\Delta kL_{P2}=21\pi$. Again, in the quasi linear regime, at low intensity, the beam broadened because of diffraction inside the crystal. By increasing the incident intensity, in nonlinear regime, we succeeded in exciting a single spatial soliton and we observed its spatial emission. The beam experienced an intensity dependent effective spatial acceleration and consequently spatial velocity in the transverse dimension (x) but with opposite direction compared to the first experiment. Because of the positive/positive phase mismatch conditions, the potential due to the nonlinear interface repulses the soliton beam toward region which exhibits the lowest phase mismatch (P2 region). In Fig. 4, typical numerical and experimental results are shown.

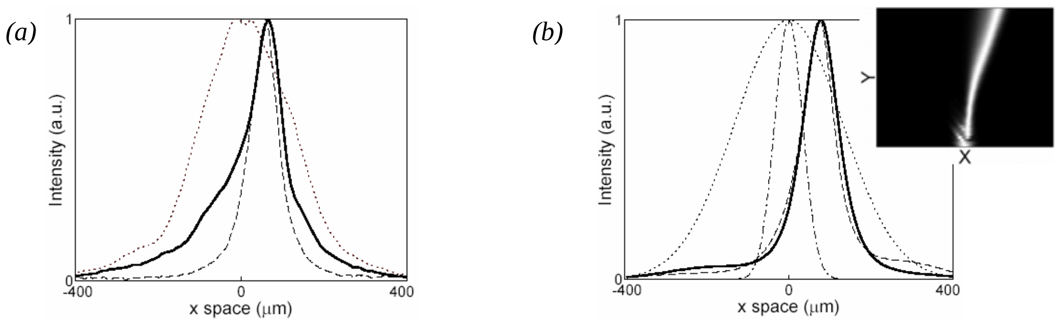

Figure 4. (a), measured and (b), calculated spatial output profiles, taken at T=185°C: FF beam in linear regime (dot curve); FF beam (solid curve) and SH beam (dash curve) at $I=160MW/cm^2$. The dash-dot curve in (b) represents the FF input profile. The inset shows the numerical FF spatial soliton evolution in the (x,y) plane, at $I=160MW/cm^2$.

Finally, we fixed temperature T at 196°C. The phase-mismatch conditions in the two uniform regions are $\Delta kL_{P1}=3\pi$ and $\Delta kL_{P2}=33\pi$. In the quasi linear regime, at low intensity, the beam broadened because of diffraction inside the crystal. By increasing the incident intensity, in nonlinear regime, we observed the breakup of the beam, and the excitation of two spatial particles. The two particles experienced opposite effective spatial acceleration and velocity towards the P2 and P1 regions.

The phenomenon of nonlinear emission can be attributed to the existence of a nonlinear potential barrier taking place at the PPLN/PPLN interface, whose properties are intensity and phase-mismatch dependent (temperature or wavelength dependent). The phase-mismatched interface does not affect low-amplitude waves. These phenomena are genuine quadratic soliton features.

CONCLUSION

In conclusion, we have observed bi-directional spatial emission of picosecond signals at 1549nm, at a quadratically nonlinear interface in periodically poled lithium niobate waveguides. We showed the intensity and phase-mismatch dependence of the phenomena. These observations make possible several soliton processing schemes, including the power-controlled steering and/or the wavelength-controlled (phase-mismatched controlled) steering.

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