Directional coupler with soliton-induced waveguides

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We demonstrate a directional coupler that employs two waveguides induced by two mutually incoherent photorefractive solitons propagating in parallel at close proximity. Efficient coupling from one waveguide to the other is achieved for probe beams at wavelengths much longer than that of the solitons. We study the mutual coupling as a function of distance between solitons. © 1999 Optical Society of America

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Loosely defined, optical spatial solitons are narrow beams that propagate without diffraction even when they are focused to small spots.[1] Intuitively, a spatial soliton is formed when the intensity of a beam modifies the refractive index (by means of an optical nonlinearity) in such a way that a waveguide is created, and the beam becomes a guided mode of that waveguide and thus self-traps.[2] These soliton-induced waveguides can be used to guide other probe beams. In Kerr-type nonlinear media, the probe beam is typically much weaker than the soliton that has induced the waveguide, and the soliton controls the probe.[3] Such soliton-induced waveguides are much more flexible than fabricated waveguides: One can change all the waveguide properties by changing the soliton. This kind of reconfigurable waveguide can be used in many applications in beam control and optical steering systems.[4]

Among the various types of spatial soliton that have been found thus far, photorefractive solitons appear to be unique, insofar as soliton-induced waveguiding is concerned.[5–7] First, photorefractive solitons form at microwatt and lower optical power levels. Second, the photorefractive effects are wavelength sensitive, which means that a soliton formed by a low-power beam can guide an intense beam of a less photosensitive (typically longer) wavelength. In addition, photorefractive solitons are stable in both 1 + 1 and 2 + 1 dimensions, which enables three-dimensional waveguiding structures, i.e., optical "fibers," to be induced into the volume of a bulk medium. Finally, photorefractive soliton-induced waveguides are fixable; i.e., it is possible to impress their structure into the crystalline lattice so that the structure remains permanently,[8] yet it is always possible to erase and overwrite this impression by electrically repoling the crystal or by bringing its temperature near a crystalline phase transition.[8]

One important application of waveguides, integrated optics, or optical fiber networks is directional couplers. A directional coupler typically consists of two waveguides at close proximity, which couple to each other by evanescent fields. In principle, in a directional coupler consisting of two completely identical waveguides, as much as 100% of the energy can transfer from one waveguide to the other after a certain propagation distance. Here we propose and demonstrate experimentally a directional coupler that uses two photorefractive soliton-induced waveguides. We use two identical parallel solitons to form a coupler and study the coupling as a function of the separation between the solitons.

In light of the benefits of utilizing solitons for directional coupling applications, one needs to keep in mind that actually realizing such a device poses one basic challenge: When two solitons propagate at a close proximity, they interact; i.e., they may attract, repel, or transfer energy to each other, depending on their relative phase.[1] The propagation direction of the solitons is directly affected by the interaction, and the solitons bend their trajectories. Thus, propagating two mutually coherent parallel solitons at close proximity is inherently impossible. However, the phase-sensitive interaction between solitons can be reduced considerably if the solitons are mutually incoherent. This means that, whereas each soliton is a coherent entity in itself,[9] the relative phase between the solitons varies much faster than the response time of the nonlinear medium.[10] The attractive force between two such mutually incoherent solitons is considerably weaker than the coherent force between the same solitons separated by the same distance. This is so because, in the coherent case, the interaction is driven by interference, whereas in the incoherent case the interaction results from a simple sum of intensities.[1] Thus it is possible to bring two mutually incoherent solitons close to each other while maintaining near parallelism between them. In this way we launch almost-parallel mutually incoherent photorefractive screening solitons at the closest proximity possible that still permits parallelism.[11]

From the argument made above, however, it is obvious that the wave functions of the solitons have little overlap. Therefore, if we use the parallel soliton-induced waveguides to guide probe beams of the same wavelength as that of the solitons that have formed the waveguides, the directional coupling is weak. This means that full energy transfer from one waveguide to another will require a large distance. To get higher coupling efficiency we have to use longer wavelengths, for which the confinement of the (lowest) guided modes

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is relatively low, so the overlap integral of these modes is much higher and results in efficient directional coupling. In our experiment, the wavelength of the probe beam is roughly twice the wavelength of the solitons, which also takes advantage of the low photosensitivity at the probe's wavelength.

In our experiment we use an SBN:60 crystal. The optical beams propagate a distance of 4.5 mm along a crystalline a axis, and the external voltage is applied along the c axis. Thus we employ the $r_{33} = 330$ pm/V ($\lambda = 488$ nm) electro-optical coefficient. We use two e-polarized 488-nm laser beams to generate two $(1 + 1)$-dimensional solitons by using cylindrical lenses, with a broad o-polarized beam as the background illumination. The two soliton-forming beams are made incoherent to each other[12] and are launched in parallel into the crystal. An extraordinarily polarized Ti:sapphire-laser 980-nm probe beam is cylindrically focused onto the input face of the crystals and used to test the coupling between the two waveguides.

First we generate a single soliton and test the induced waveguide. The beam is focused to a FWHM of 13 μm along the c axis, while it is kept uniform along the a axis at the input surface of the crystal. After 4.5-mm propagation, it diffracts to 34 μm at the output surface. The intensity ratio (between the soliton-forming beam and the background illumination) is 1.8. The soliton is formed when we apply a voltage of 800 V and attains the same FWHM as at the input. We then launch a 24-μm FWHM probe beam into the induced waveguide. We use a wider input beam because, for the same waveguide, the confinement of the lowest guided mode for the longer wavelength of the probe is weaker. When the voltage is on, the probe beam is guided well.

Next we generate a directional coupler by launching two mutually incoherent solitons such that the interaction between the solitons is so weak that the trajectories are almost fully parallel. The peak-to-peak separation between the input two solitons is 30 μm, and at the output the solitons are 32 μm apart [Fig. 1(a)], i.e., almost fully parallel. The intensities and the widths of the two beams are nearly identical, and both solitons are formed when we apply a voltage of 800 V. First we study the energy exchange between the solitons by means of the incoherent interaction[6,7] and examine each output soliton separately by blocking one input soliton and observing the other's output within a time window much shorter than the crystal's response time.[12] As shown in Figs. 1(b) and 1(c), there is little energy coupled from each soliton into the waveguide induced by the other soliton. This means that, were the probe beam at the same wavelength as the solitons, we could expect only weak directional coupling. Then we launch the probe beam into the left (first) soliton only, and observe that a large portion of the energy has coupled from the original waveguide into the other waveguide, as shown in Fig. 1(d). The coupling efficiency (the fraction of energy transferred by directional coupling) is ~45%. For comparison, when only the left soliton exists (into which the probe is launched) and the crystal is at steady state for a single-soliton input, the probe beam is guided well by the single waveguide [Fig. 1(e)]. On the other hand, when only the right soliton is present, and the probe beam is still launched into where the left soliton had been, the probe is not guided but diffracts [Fig. 1(f)], and only a tiny part of its energy is trapped by the adjacent waveguide induced by right soliton [the little bump at the right of the diffracted beam in Fig. 1(f)]. All these results show that the coexistence of two solitons works as a directional coupler and that the probe beam is coupled from one soliton-induced waveguide into the other.

To study the relation between the directional coupling and the separation between the solitons, we vary the position of the second soliton and test the coupling as a function of soliton separation, as shown in Fig. 2. When the two solitons are 50 μm apart, no coupling is observed [Fig. 2(a)]. When the separation is 40 μm, roughly 20% of the probe beam is coupled from the left into the right waveguide [Fig. 2(b)]. When the separation is 30 μm, the coupling increases to 45% [Fig. 2(c)]. When the separation is 25 μm,

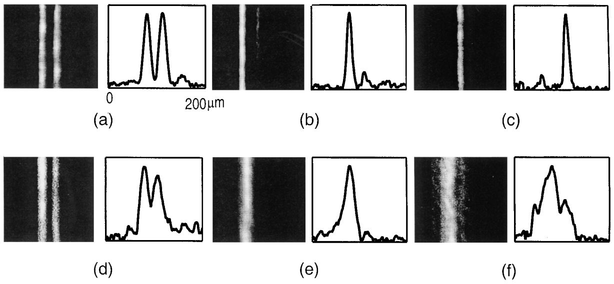

Fig. 1. Photographs and profiles of (a) both output solitons, (b) left soliton output when the right soliton is blocked for a time window much shorter than the response time of the nonlinearity, (c) as in (b) but with right and left solitons exchanging roles, (d) output probe beam when both solitons are on, (e) output probe when only the left soliton (into which the probe is launched) is present, (f) output probe when only the right soliton is present and the probe is launched into where the left soliton had been.

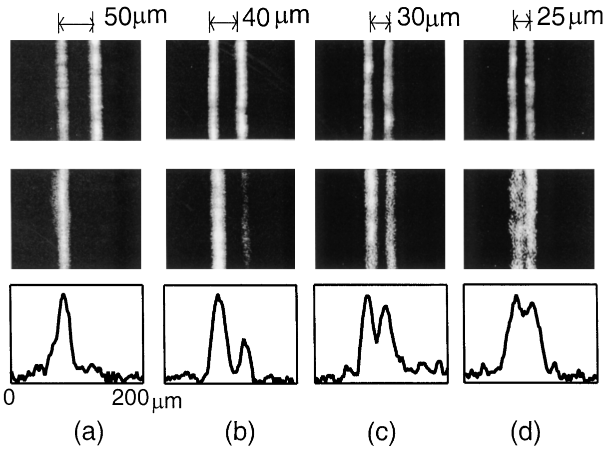

Fig. 2. Photographs of the soliton beams (top) and photographs and profiles of the probe beams (which are all launched into the left soliton; middle and bottom) exiting the crystal, for various separation distances between the solitons.

the output probe beams almost fully merge [Fig. 2(d)]. This is so because the lowest guided modes for the 980-nm beam in the two waveguides overlap each other and are almost indistinguishable. Therefore, clear coupling from one waveguide to another cannot be obtained.

It is instructive now to compare the experimental results with theoretical estimates. Consider a symmetric directional coupler, which is a special case of the general problem analyzed in Ref. 13. We assume that the soliton-induced waveguides are fully parallel to each other and calculate their shape by using the theory given in Ref. 7. That is, we do not assume step-index waveguides (as in Ref. 13) but rather find their actual shape for the specific case of screening solitons. We measure, in a separate interference experiment, the maximum index change at the probe wavelength ($\lambda = 980$ nm) and find that $\Delta n_{\max} = {n_e}^3 r_{33} V/(2l) \approx 0.00026$. Our solitons had an intensity ratio of 1.8; thus we can safely approximate the shape of the lowest guided mode in their respective waveguides as a hyperbolic secant. Using the probe-beam widths employed in the experiment and 31-μm separation, we find that after 4.5-mm propagation the coupling efficiency is roughly 38%, very close to the experimental value.

In conclusion, we have demonstrated that two mutually incoherent spatial solitons propagating in parallel at close proximity can serve elegantly as a directional coupler for light at a longer wavelength. The maximum coupling efficiency observed in our experiments was 45% for solitons at $\lambda = 488$ nm, the probe at $\lambda = 980$ nm, and a propagation length of 4.5 mm. We fully expect that for probe beams at optical communication wavelengths, or for a larger propagation length, the coupling efficiency can be almost unity.

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