give the lowest loss at 10.6 μm. We note the excellent agreement between theory and experiment at this wavelength. In particular, the data indicate that not only is the measured loss for this structure as low as possible but also that these guides are essentially single mode. This means that the light output may be reimaged to a small spot size—an important feature for many surgical and industrial applications which require preservation of the laser beam profile.

The most important applications for these waveguides are for short-haul (< 10 m) sensor and power delivery. We have used the guides for gas sensing by filling the hollow core with gas, blackbody temperature measurement, and the transmission of laser radiation in a laser threat-warning receiver. As a power delivery waveguide, the device has delivered as high as 1010 W of CO_2 laser radiation from a 700 μm-bore guide equipped with an external water-cooling jacket and 10 W of Er:YAG laser power. In general, these hollow guides are flexible, robust, and inexpensive to fabricate, and, therefore, they should be useful in many sensor and power delivery applications.[2]

References

1. T. Abel *et al.*, "Hollow glass waveguides for broadband infrared transmission," Opt. Lett. **19**, 1034-1036 (1994).
2. J.A. Harrington, "Review of hollow waveguide technology," *Biomedical Optoelectronic Instrumentation*, Proc. SPIE, J.A. Harrington *et al.*, eds., **2396**, 4-14 (1995).
3. Y. Matsuura *et al.*, "Small-bore hollow waveguide for delivery of near singlemode IR laser radiation," Electron. Lett. **30**, 1688-1690 (1994).

Observation of Two Dimensional Spatial Solitary Waves in a Quadratic Medium

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Using intense fields, newly developed second order materials, such as KTP, which show a quadratic response with the optical field, can produce large phase distortions.[1] Such effects are more commonly associated with an ultrafast change in the refractive index following the intensity of light. In a few materials with large second order response such as KTP, the coupling (energy exchange) between the fundamental and second harmonic fields can be the dominant process inducing large phase front distortions.

Under the appropriate phase matching conditions one can induce a positive lens. The question arises, "Can such a lens compensate for the natural diffraction of light?" The answer to such a question was first provided in 1976.[2] Indeed the optical Kerr effect under the so-called paraxial regime is known to exhibit unstable behavior and, in general, produce catastrophic self-focusing effects. Because the nonlinear phase change in a quadratic process, such as second harmonic generation, can, in the strong coupling regime, follow the amplitude and not the intensity of the fundamental optical field, stable multidimensional solitary waves (soliton-like) can be predicted to occur in state-of-the-art quadratic bulk crystals.[3,4]

We have recently demonstrated experimentally that solitary waves can occur in KTP, a widely commercially available second order material.[5] The experiment consisted of focusing 30 psec (FWHM) Nd:YAG laser pulses onto a spot with a radius of approximately 20 μm, corresponding to five diffraction lengths in the 1 cm long crystal. Near the phase matching condition, the energy exchange between the fundamental and second harmonic fields was large enough to induce a phase distortion which locked, both the fundamental and second harmonic beams in space, defeating diffraction and spatial walk-off induced by the natural birefringence of the material. The latter process, "solitary-wave-locking," was present under a wide range of experimentally achievable parameters. For instance, the phase mismatch between the input fields was varied between -5π and +5π, the input fundamental intensity was varied over one order of magnitude, and the process could also be seeded with an input second harmonic beam. In all cases "solitary-wave-locking" was achieved. The accompanying figure shows that at low input intensities diffraction dominates and the peak intensity diffuses with distance. However, as the intensity reaches a given threshold, the nonlinear length exceeds the diffraction length, the crystal is then long enough to back-convert the appropriate portion of

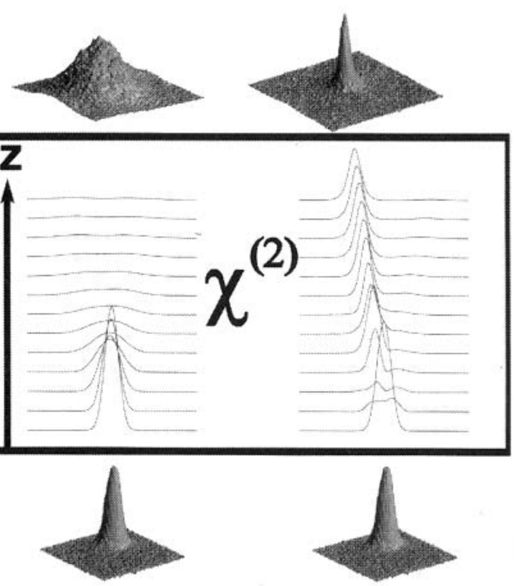

Figure 1. The numerical evolution of the fundamental beam below and above the 2-D "solitary-wave-locking" threshold. The 3-D plots are experimentally measured beam profiles while the solid curves represent our numerical simulations of the process.

the second harmonic field into the fundamental. The coupling is then strong enough to produce soliton-like beams mutually trapped.

"Solitary-wave-locking," we believe, will have a tremendous impact in the future design of second harmonic generators and tunable optical parametric sources, improving their stability and overall optical beam quality. In addition, it represents an invaluable testbed for the investigation of ultrafast multidimensional solitary wave physics.

Acknowledgments

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References

1. R. deSalvo *et al.*, "Self-focusing and self-defocusing by cascaded second-order effects in KTP," Opt. Lett. **18**, 28 (1992); G.I. Stegeman *et al.*, "Large nonlinear phase modulation in quasi-phasematched KTP waveguides as a result of cascaded second order processes," Opt. Lett., **18** 1397 (1993).
2. Y.N. Karamzin and A.P. Sukhorukov, "Large nonlinear phase-shifts in second order nonlinear optical processes," Sov.Phys.-J.E.T.P., **41**, 414 (1976).
3. K. Hayata and M. Koshiba, "Multidimentional solitons in quadratic nonlinear media," Phys. Rev. Lett. **71**, 3275 (1993).
4. L. Torner *et al.*, "Two-dimensional solitons with second order nonlinearities," Opt. Lett. **20**, 13 (1995).
5. W.E. Torruellas *et al.*, "Observation of two-dimensional spatial solitary waves in a quadratic medium," Phys. Rev. Lett. **74**, 5036 (1995).

COMMUNICATIONS

Transmission of Eight 20 Gb/sec Channels over 232 km of Conventional Single-Mode Fiber

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Installed telecommunication lightwave systems are now being upgraded with erbium-doped-fiber-amplifier (EDFA) optical repeaters. Less expensive than full regenerators which receive, reshape, and re-transmit the optical signal, the EDFAs also allow future capacity increases through the use of wavelength-division multiplexing. These amplifiers operate at approximately 1555 nm, where the loss of conventional step-index fiber, used in almost all installed systems, is a low 0.2 dB/km. However, the fiber exhibits dispersion of 17 psec/nm•km at this wavelength. This restricts the transmission distance that can be reached before a signal must be regenerated to avoid incurring an unacceptable penalty from dispersion-induced distortion. For a transform-limited signal, the distance at which a 1 dB penalty is reached is inversely proportional to the square of the bit-rate—about 1000 km at 2.5 Gb/sec, 65 km at 10 Gb/sec, and 16 km at 20 Gb/sec.[1]

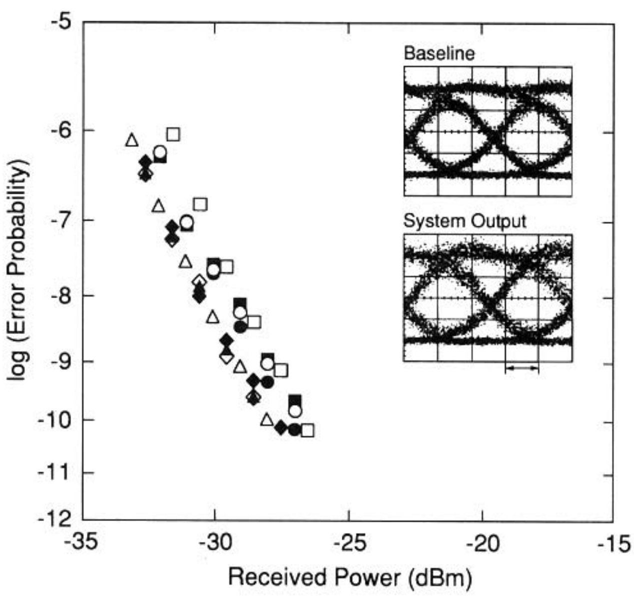

Figure 1. Bit-error-rate data for all eight channels after 232 km. Inset shows eye pattern at system input and output.

Laboratory and field demonstrations of upgrades have therefore followed two paths. Wavelength multiplexing of several 2.5 Gb/sec channels[2] has allowed unregenerated spans of hundreds of kilometers. Alternatively, higher bit-rate systems have been realized using shorter regenerator spacings or dispersion compensation. Recently[3] 10 Gb/sec transmission over 360 km of conventional fiber was achieved in a field trial using dispersion-compensating fiber (DCF). In this paper, we demonstrate that the strategy of dispersion compensation at a bit rate of 20 Gb/sec can be combined with extensive wavelength multiplexing. Eight 20 Gb/sec channels, spaced 200 GHz (1.6 nm) apart and centered around 1555 nm, have been transmitted over 232 km of conventional single-mode fiber. In addition to having negative chromatic dispersion of up to 100 psec/nm•km, the dispersion-compensating fiber used in this experiment,[4] also exhibits a negative dispersion slope. This partially compensates for the dispersion slope of the transmission fiber, resulting in an effective dispersion slope for the 232 km span of 0.02 psec/nm^2•km, compared to 0.08 psec/nm^2•km for the conventional fiber itself. This allows penalty-free transmission at 20 Gb/sec over the entire 11.2 nm bandwidth of the system.