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Novel Photonic Materials for Advanced Imaging Applications

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This contribution reviews some recent work in the development of novel composite materials for nonlinear optics, the development of structured waveguides with exotic optical properties, and the development of some advanced imaging techniques.

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I. NEED FOR NEW PHOTONIC MATERIALS

Some of the exciting potential applications of nonlinear optics include quantum computing, quantum communications, quantum imaging, all-optical switching, optical power limiting, and nonlinear optical image processing. However, the implementation of these applications has historically been held back by the limited availability of materials with the required properties of large optical nonlinearity combined with high optical transparency and high resistance to laser damage. Several strategies have traditionally been exploited in an attempt to create new materials with more desirable optical properties. These strategies include the synthesis of new chemical compounds with intrinsically large optical response, the use of quantum coherence techniques to more efficiently utilize the nonlinear response present in a given material, and the creation of composite materials that can combine the desirable characteristics of two or more constituent materials to create a new material with tailored optical properties.

Of particular interest is the hope of developing artificial materials and structures with optical properties fundamentally unlike those of naturally occurring materials. Some of the exotic characteristics these devices can be expected to display include ultra-slow and superluminal group velocities of propagation, enhanced optical nonlinearities, and large dispersion with a controllable magnitude and sign.

II. COMPOSITE MATERIALS FOR NONLINEAR OPTICS

Composite optical materials can display useful optical properties that are qualitatively dissimilar from those of their underlying constituents. Nanocomposite materials are especially well suited for photonics applications because they can be constructed in such a manner as to produce enhanced nonlinear optical response. Some such materials are formed by a random association of the underlying constituents, whereas other are formed with deterministic properties through various fabrication methods. Work on the development of composite materials has recently been reviewed in reference [1].

The experimental system that we used to first demonstrate enhanced nonlinear optical response of composite materials consists of alternating layers of the conjugated polymer PBZT and of titanium dioxide. Layers were spin coated with a thickness of approximately 50 nm and were cured at elevated temperatures. After curing, PBZT has a refractive index of 1.65 and titanium dioxide a refractive index of 2.2. The third-order susceptibility of PBZT is several orders of magnitude larger than that of titanium dioxide. These samples were studied experimentally by measuring the nonlinear refractive index experienced by an intense light beam using the induced focusing technique. Some of our results [2] are shown in Fig. 1. We measured the nonlinear phase shift as a function of the angle of incidence. These results are in quantitative agreement with the theoretical prediction that effective nonlinear susceptibility of the composite material for p polarized light is 35 % larger than that of the pure nonlinear material.

The enhancement achieved for the PBZT/titania composite was only 35 %. While an enhancement of this size is physically significant, it is not large enough to have important technological implications. We have more recently fabricated a composite electrooptic material [3] with a much larger enhancement of a factor of 3.2. The material is illustrated in Fig. 2. It consists of alternating layers of rf-sputtered barium titanate and spin-coated polycarbonate containing a third-order nonlinear optical organic dopant. The effective nonlinear susceptibility of the composite describing the quadratic electrooptic ef-

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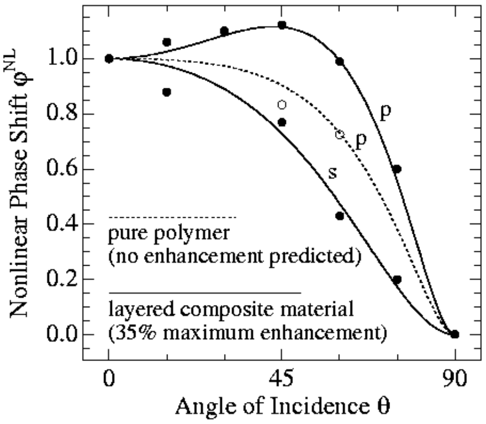

Fig. 1. Measurement of enhanced nonlinear optical response of a composite nonlinear optical material.

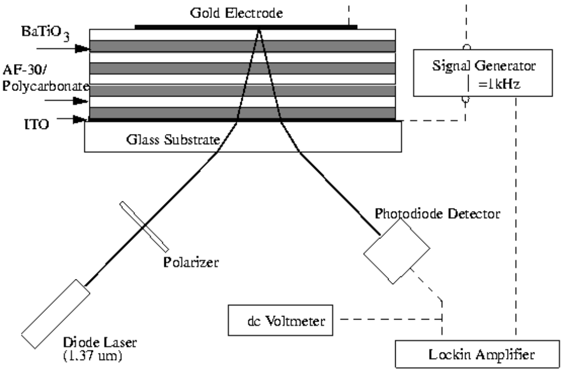

Fig. 2. Sample geometry and experimental arrangement used to study an electrooptic composite material. The measure nonlinear response is 3.2 times that of the pure nonlinear material.

fect was measured to have the value $3.2 + 0.2i\times10^{-21}$ $(\mathrm{m/V})^2$. The real part of this value is a factor of 3.2 times larger than that of the doped polycarbonate, which is the dominant electrooptic component of the composite.

III. NANOSTRUCTURED WAVEGUIDES FOR NONLINEAR OPTICS

Some of our more recent work has been devoted to the development of artificial materials in the form of structures consisting of waveguides coupled to arrays of optical resonators. One of the structures that we are presently investigating [4] is shown in part (a) of Fig. 3. It consists of an optical waveguide coupled to a series of optical resonators. The resonators can be of arbitrary design, although in our experimental work we are concentrating on resonators in the form of a ring waveguide or a whispering gallery mode of a disk. A pulse of light is shown propagating through this structure. Evanescent coupling between the waveguide and resonator injects light into each resonator where it circulates many times (on resonance, $2F/\pi$ times, where F is the finesse of the resonator) before being coupled back into the waveguide. For a densely packed collection of high-finesse resonators, a light wave spends much more time circulating within each resonator than in propagating between resonators. Thus the group velocity of propagation can become very small. Because the time delay acquired in interacting with each resonator depends critically on the detuning of the optical wave from the resonance frequency, this device displays tailorable dispersion with a size that is many order of magnitude larger than that of conventional materials. Also, because of the build-up of intensity within each resonator, the nonlinear response of this structure is greatly enhanced. We have shown [5] that the nonlinear response is enhanced in comparison to propagation through a bulk nonlinear material by the square of the resonator finesse. Under appropriate conditions, these dispersive and nonlinear effects can precisely balance one another, leading to the propagation of optical solitary waves. Some examples of the predicted behavior are shown in Fig. 4.

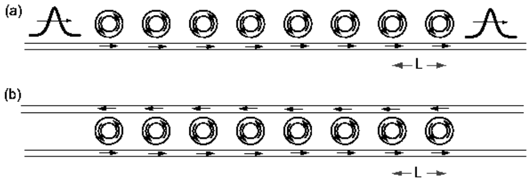

Fig. 3. Structured waveguides to be studied as part of this program and which displays slow light propagation, large controllable dispersion, and large controllable nonlinearity. (a) Single-guide structure and (b) double-guide structure.

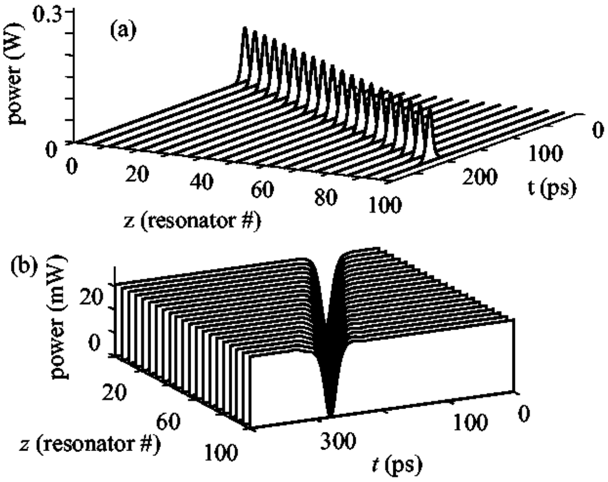

Fig. 4. Because the sign of the group-velocity dispersion for the device shown in Fig. 2(a) can be controlled by varying the optical frequency, both bright (upper panel) and dark (lower panel) optical solitons can be made to propagate through the same physical device.

A related structure is shown in the Fig. 3(b). It consists of upper and lower waveguides coupled to the same sequence of resonators [6]. The optical properties of such a device differ in fundamental ways from those of the single-guide structure. Because forward and backward going waves are coupled in the two-guide structure, it possesses a photonic bandgap, which is not present in the single-guide structure. Both structure are expected to possess useful photonic properties, which however differ in their detailed behavior. We are studying the fundamental optical properties of structures of this sort, although we expect them to have important implications for applications such as soliton propagation, controllable optical delay lines, and photonic switching.

IV. QUANTUM AND NONLINEAR OPTICS FOR ADVANCED IMAGING APPLICATIONS

Research performed over the past decade has demonstrated the utility of using quantum states of light to perform measurements with unprecedented accuracy and sensitivity. A well known example is the use of squeezed states of light to perform measurements with an accuracy in excess of the classical shot-noise limit. More recently entangled states of light have been used to perform functions unthinkable in the context of classical physics, such as the demonstration of quantum cryptography and quantum teleportation. However, for the most part past research has dealt primarily with the quantum states of single-transverse mode optical fields. Such fields fail to make use of the enormous information content achievable in the transverse structure of an optical field. Our research addresses this aspect of modern quantum optics by examining means of generating squeezed and entangled states of light in beams containing many transverse modes. Through use of these new field states, we will perform laboratory investigations of techniques to perform imaging operations with a sensitivity and/or resolution that greatly exceeds that achievable with classical techniques.

Our research program entails the development of laboratory techniques to generate multimode squeezed and entangled states of light and to use of these quantum states of light in the development of imaging systems with enhanced performance characteristics. One application entails the development of techniques for the construction of imaging systems that can achieve a transverse resolution that exceeds the classical Rayleigh criterion [7–9]. This approach is based on the unusual interference phenomena that can be observed from highly entangled light fields, as illustrated in Fig. 5.

Most previous work on the development of quantum states of light has utilized second-order nonlinear optical interactions. In contrast, we are interested in using third-order nonlinear optical interactions for this purpose, as illustrated in Fig. 6. Such interactions hold particular promise for quantum imaging for reasons including the fact that they can produce quantum states of light without producing a large wavelength shift on the generated beam. We have recently observed spontaneous pattern formation based on a third-order interaction and have measured strong correlations of the intensity fluctuations for various points within the generated pattern [10]. Some of these results are shown in Fig. 7. We have also recently performed investigations that clarify the role of classical correlations versus quantum entan-

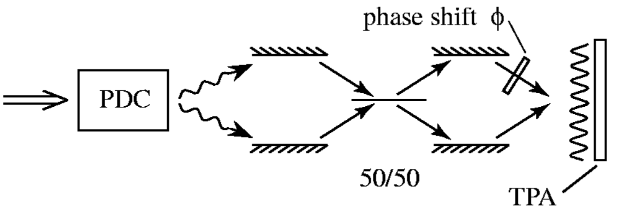

Fig. 5. Schematic experimental setup that can be used to record interference fringes with a spacing twice as dense as predicted by classical interference. This techniques has crucial implications for lithography and microscopy.

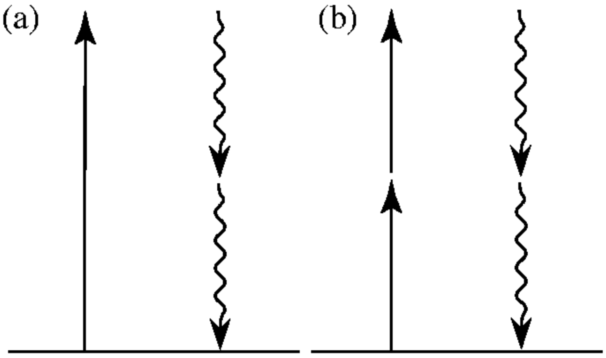

Fig. 6. Although much work on the generation of quantum states of light makes use of second-order nonlinear optical interactions (a), we propose to make use of third-order interaction (b), which possess superior characteristics under many circumstances as described in the accompanying text.

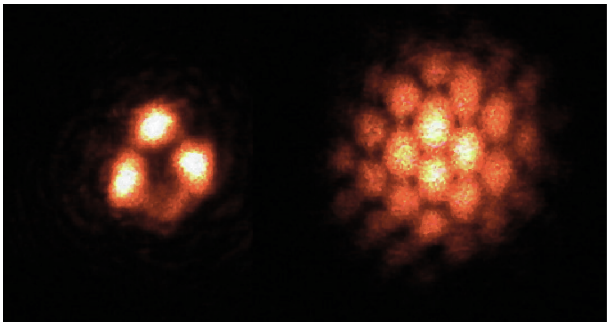

Fig. 7. Experimental results showing spontaneous pattern formation in the propagation of a laser beam through a sodium vapor cell. There are theoretical reasons to hope that strong transverse quantum correlations are present in structures of this sort.

glement in the context of two-photon coincidence imaging [11].

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