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Distributed feedback laser action by polarization modulation

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ABSTRACT Laser action was generated in dye-doped sol–gel glass waveguides and in liquid solutions by crossing two beams from a frequency-doubled neodymium:YAG laser. The angle between the polarization directions of the two beams was varied continuously from 0–90°. The case of 0° corresponded to pure intensity modulation. As the angle increased, the degree of intensity modulation decreased, resulting in the decline and finally the demise of the laser output. At 90°, corresponding to pure polarization modulation, distributed feedback laser action with narrow line-width output was again observed when the pump energy was increased three-fold. The laser output also showed different polarization characteristics when the feedback mechanism was changed from intensity modulation to polarization modulation.

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Distributed feedback (DFB) laser action is made possible by the presence of periodic perturbations in the gain medium that provide feedback by backward Bragg scattering [1]. The periodic perturbations can be effected by the spatial modulation of the refractive index [1] or gain or a combination of both [2]. In a waveguide structure, a periodic change of the guiding film thickness was also proven effective in inducing DFB laser action [3]. The periodic perturbations can be permanent or transient, with the transient effect often produced by crossing two beams from the output of the same laser to generate a concentration grating [2, 4]. A coupled-wave theory based on the scalar wave equation has been developed to describe the DFB laser phenomenon [5].

A schematic of a typical crossing beam experiment is illustrated in Fig. 1. The two beams are shown to have their polarization directions at an angle Φ.The crossing beams must have an s-polarized ($\Phi = 0°$) component for the formation of an intensity interference pattern (intensity modulation). The intensity interference pattern in the gain medium produces a concentration grating of excited-state atoms/molecules, which is to provide the periodic change in gain or refractive index necessary for DFB laser action. The crossing of an s-polarized beam with a p-polarized beam ($\Phi = 90°$) does not produce an intensity interference pattern. No spatial modulation of atom/molecule concentration could result in the gain medium. Instead a periodic change of the polarization (polarization modulation) of the resultant field, which changes from linear polarization to elliptical polarization to circular polarization and then back to elliptical polarization after one period, is created [6]. The excited-state atoms/molecules align themselves along the preferred direction of the polarization across the gain medium. The grating that results from polarization modulation is a polarization grating. The phenomena of polarization gratings in dye-doped materials have been studied for applications in holographic recording [7] and in pump-probe experiments to study orientation relaxation of molecules [8]. The polarization effects of DFB lasing during optical pumping have been reported in [9, 10].

We report in this paper that a transient polarization grating resulting from polarization modulation can be used to generate DFB laser action. This is a mechanism that cannot be described by coupled-wave theories based on the scalar wave equation, since polarization modulation produces no change in the scalar amplitude of either the gain or the refractive index in the gain medium. Rather, it is the induced optical anisotropy of the gain medium that provides the periodic perturbations needed for DFB lasing. DFB laser action induced by polarization modulation was observed in both rhodamine 6G (R6G)-doped sol–gel glass waveguides and in R6G–ethanol solutions, demonstrating the effectiveness of polarization modulation in solids and in liquids. The DFB laser output also showed different polarization characteristics in intensity modulation and in polarization modulation. In liquids, the DFB laser output is essentially s-polarized when induced by intensity modulation. It becomes elliptically polarized when polarization modulation is used. In waveguides, the manifestation of the change in output polarization is the transition of a single TE_0 to a pair of TE_0/TM_0 output modes.

The first experiments with a DFB laser were performed on R6G-doped sol–gel glass waveguides. The sol–gel technique based on inorganic chemical precursors was used to prepare dye-doped zirconia thin-film waveguides. The fabrication procedures for sol–gel-derived zirconia and zirconia-organically modified silicate films have been described in [11] and will not be elaborated here. In the laser experiments to be presented in the following sections only zirconia films on glass substrates were used. Good-quality dye-doped zirco-

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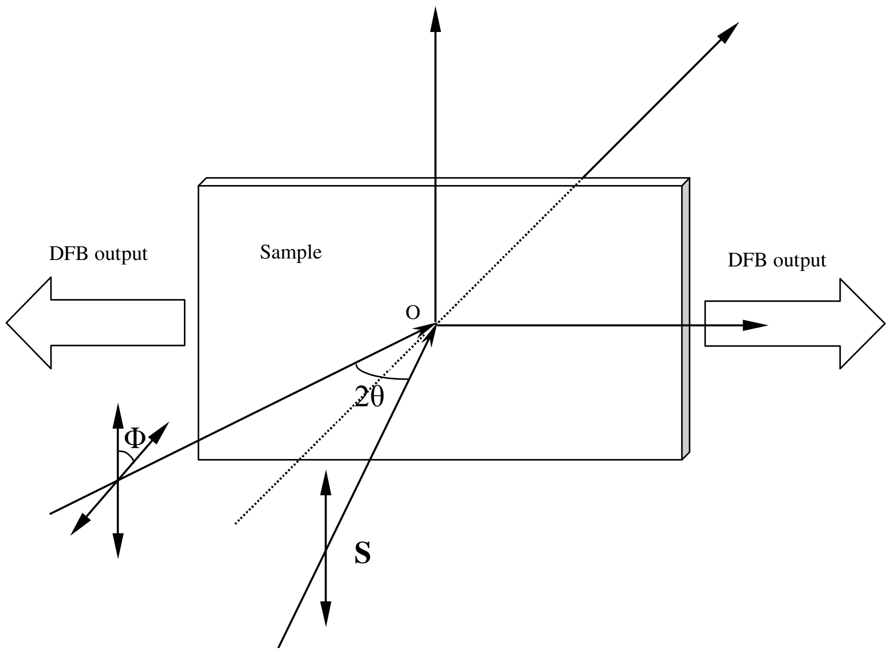

FIGURE 1 Schematic of the crossing beam experiments. The polarization of one of the beams is at an angle Φ with respect to the s-polarization. The other beam is s-polarized

nia films of a thickness of 0.6 μm and a refractive index of 1.57 on glass substrates (refractive index of 1.51) were obtained by dip coating. The typical dye concentration in the zirconia films was 3×10^{-3} M/l. The concentration was optimized for good DFB laser signal to amplified spontaneous emission (ASE) background ratio. The wave-guiding properties of doped zirconia films were characterized using a prism coupler (Metricon model 2010). These 0.6 μm zirconia films were shown to support a pair of TE_0/TM_0 modes. The experimental arrangement for DFB waveguide laser experiments was similar to that in our earlier work on an ultra-violet sol–gel glass DFB laser [12], the changes being the introduction of polarization optics (viz. wave plates, Glan–Taylor prisms, etc.) in the optical paths to manipulate the polarization directions of the crossing beams. Briefly, the s-polarized output from a frequency-doubled nano-second Nd:YAG laser was split into two beams by a beam splitter. One of the beams was converted to have circular polarization using a quarter-wave plate, whilst the other beam retained the s-polarized character. By passing the circularly polarized beam through a rotatable calcite Glan–Taylor prism, a linearly polarized beam with polarization direction at an angle Φ with respect to the s-polarized beam resulted (Fig. 1). The intensities of the two beams were adjusted to be of roughly equal strength using neutral-density filters. The two beams were then redirected to combine on the films at an intersection angle of $2\,\theta$ to create a periodic modulation, whose nature varies from pure intensity modulation (for $\Phi = 0°$) to pure polarization modulation ($\Phi = 90°$). For $0° \leq \Phi \leq 90°$, the modulation is a mixture of intensity and polarization modulation. The output wavelength of the DFB lasers in sol–gel glass waveguides or in liquids follows the Bragg condition $\lambda_L = \eta\lambda_p/M \sin\theta$, where η is the refractive index of the gain medium at λ_L, λ_p is the pump laser wavelength and M is the Bragg reflection order and was equal to 2 in these experiments. For DFB laser action in waveguides, η takes on the values of the effective indices for TE_0 modes or TM_0 modes. Tuning of λ_L can be achieved by varying the intersection angle and thus the modulation period. A 0.3-m spectrograph/ intensified charged coupled device (ICCD) detector system was employed for spectral measurement. The time waveforms were measured using a photo-tube and a fast digital oscilloscope.

Figure 2 shows the DFB laser emission spectra of the dye-doped zirconia waveguides as Φ changes from 0° to 90° for $\theta \approx 44°$. The pump energy used was 10 μJ. At $\Phi = 0°$, corresponding to the case of pure intensity modulation, the output shows a single-peak structure with a narrow line width, which is characteristic of the high frequency selectivity of distributed feedback lasing. Tuning of the output wavelength was readily achieved by changing θ. Separately the variation of Φ in effect changes the amplitude of the s-polarized component of the beam. As Φ increases, the effectiveness of intensity modulation weakens as the disparity in amplitude of the s-polarized components of the two crossing beams grows, resulting in a low degree of modulation in the transient intensity grating. At $\Phi = 60°$ the amplitude of the electric field of the s-polarized component is $1/2$ of the companion beam. The effect of intensity modulation is already so weakened that a substantial ASE background (ratio of DFB output intensity to ASE intensity of 10 : 3) in the emission spectrum appears. At $\Phi = 80°$ the modulation effect of the intensity grating is such that the DFB lasing peak at 600 nm is barely distinguishable from the broad ASE background. At $\Phi = 90°$ DFB lasing is completely extinguished since the s-polarized component of one of the beams has zero amplitude. Only ASE is observed. The pump energy was then gradually raised to about 30 μJ. DFB lasing reappeared at 30 μJ, but this time the feedback mechanism was provided by polarization modulation. The distinguishing feature of DFB lasing induced by the polarization modulation is the appearance of a pair of TE_0/TM_0 output modes, whereas only the TE_0 mode is observed in the case of intensity modulation. The output wavelengths of the TE_0/TM_0 mode precisely follow the Bragg condition with the mode effective indices of the

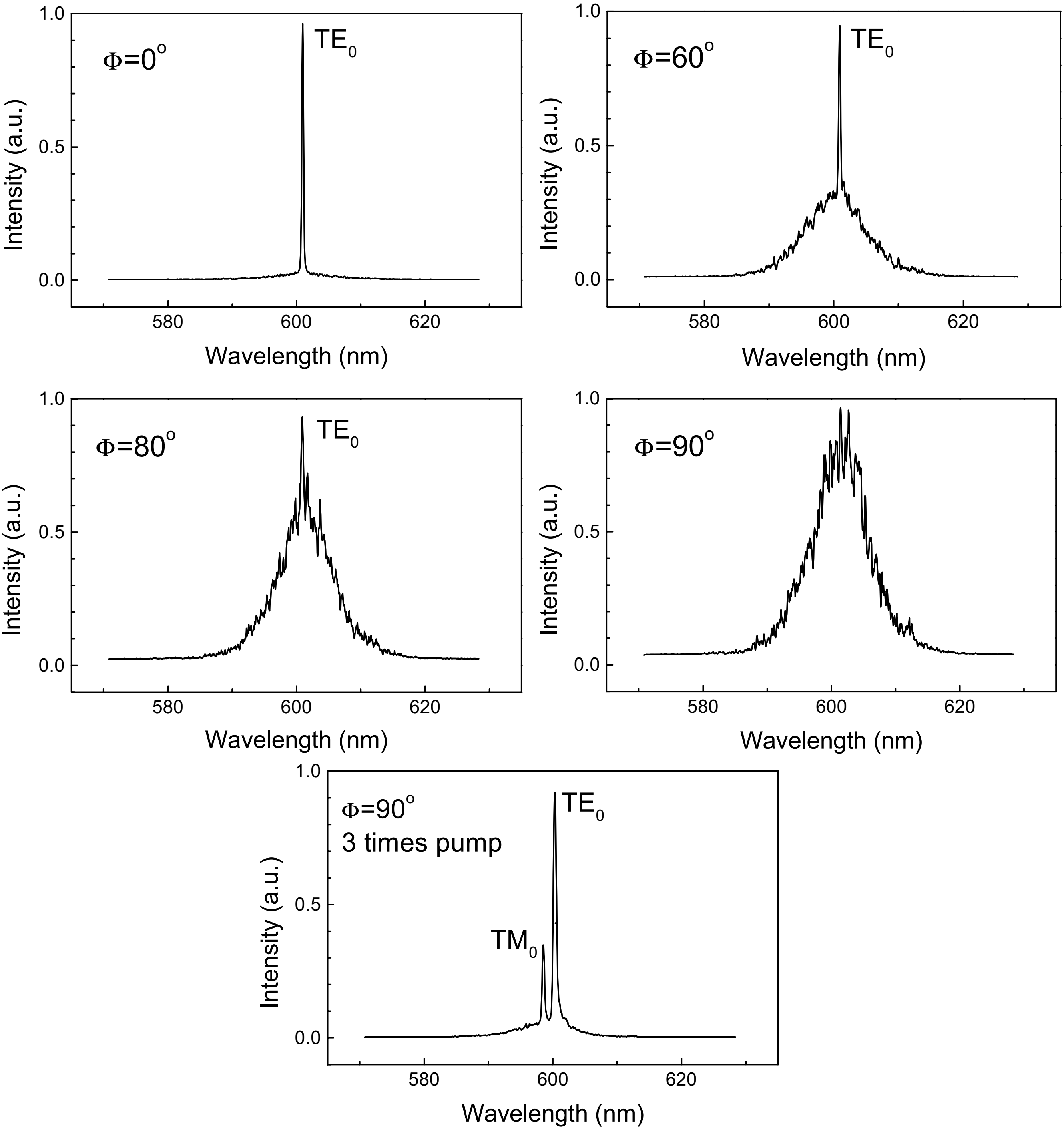

FIGURE 2 Output spectra of a DFB laser in zirconia waveguides as Φ varies

zirconia waveguide,demonstrating the high optical quality of the zirconia waveguides and the effectiveness of the polarization modulation. Tuning of the output wavelength is also possible by varying the intersection angle as in intensity modulation.

To further examine the DFB lasing behavior of polarization modulation, the same laser experiments were repeated on R6G–ethanol solutions. The dye concentration used was 6×10^{-4} M/l. Figure 3 shows the emission spectra of DFB lasing in liquids as Φ varies. θ was set at about 38° as the refractive index of the liquid was 1.359. The threshold pump energy for DFB lasing in liquids was somewhat higher than that in waveguides. The same general feature of the gradual decline of the effectiveness of intensity modulation as in zirconia waveguides is largely repeated. The DFB lasing peak shifts to 567 nm on account of the lower refractive index of the liquid. DFB lasing recovers at $\Phi = 90°$ when the pump energy was raised by three times. However, only one emission peak was observed in the output spectra. For, unlike wave propagation in waveguides, TE and TM optical waves

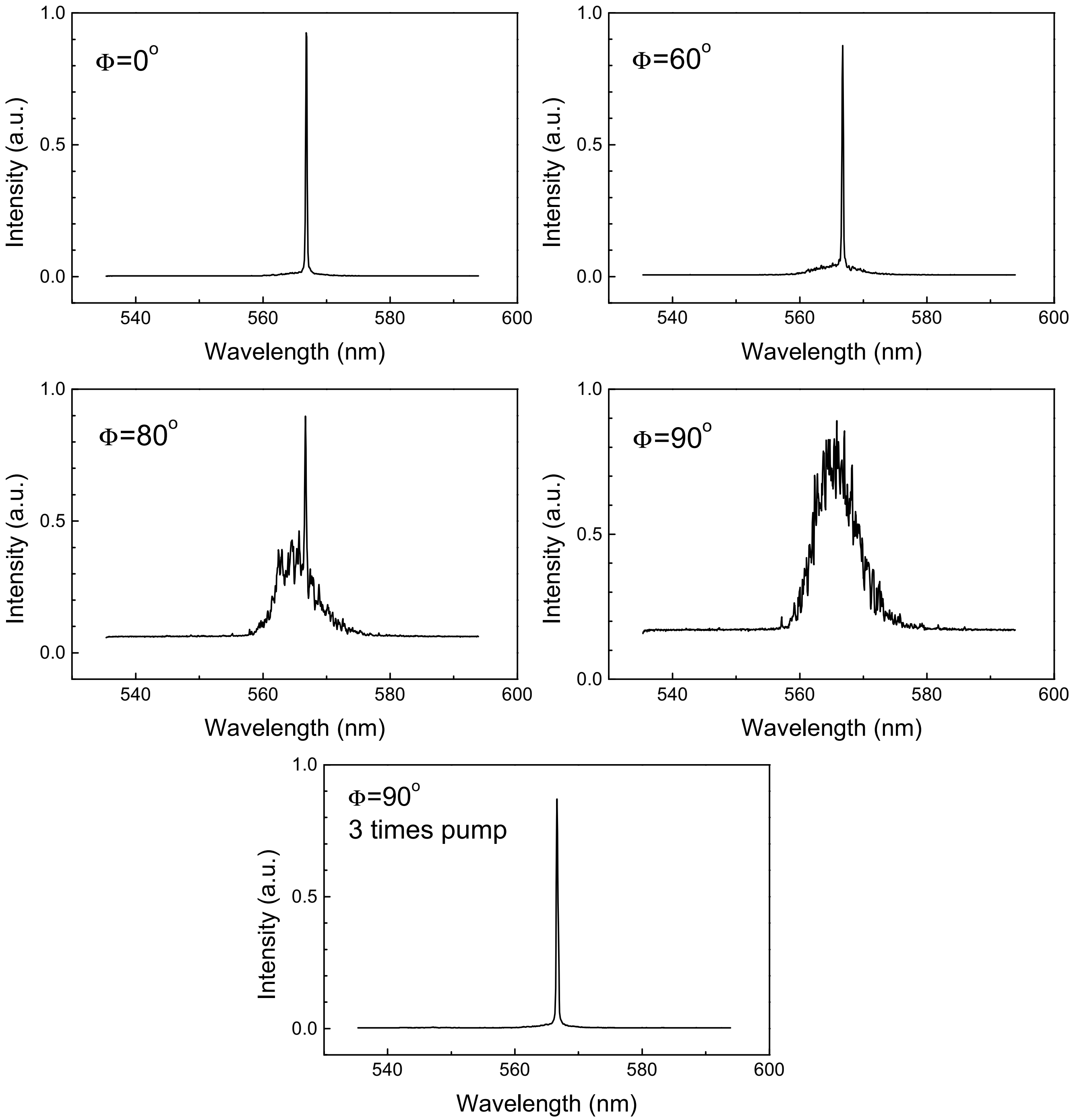

FIGURE 3 Output spectra of a DFB laser in ethanol as Φ varies

propagate at the same phase velocity in isotropic bulk matter. We also measured the ratio of the intensities of the *s*- and *p*-polarized components (*s* to *p* ratio) of the DFB laser output from liquids. The *s* to *p* ratio is $32:1$ in the case of pure intensity modulation ($\Phi = 0°$) and it becomes $5:1$ for pure polarization modulation ($\Phi = 90°$). The DFB laser output therefore changes from a linearly polarized wave to an elliptically polarized wave as the modulation varies from that of pure intensity to that of pure polarization. Since the threshold pump energy of polarization modulation is three times higher than that of intensity modulation, the intermediate cases ($0° \leq \Phi \leq 90°$) probably behave very much like that of intensity modulation.

In conclusion, we have demonstrated that polarization modulation is effective in providing feedback for DFB laser action in solids and in liquids. The state of polarization of the DFB laser output changes from linearly polarized to elliptically polarized in liquids as the modulation moves from intensity modulation to polarization modulation. In waveguides, the polarization-modulated DFB laser output consists of a pair of TE_0/TM_0 output modes, whilst an intensity-modulated DFB laser produces a single TE_0 mode.

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