Mol. Cryst. Liq. Cryst., 1996, Vol. 283, pp. 43–50
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TRANSMISSION MODULATION OF A SINGLE-MODE PLANAR WAVEGUIDE BY SPECTRAL HOLE BURNING

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Abstract We investigate persistent spectral hole burning (SHB) in a 120-nm-thick polymer film doped with chlorin molecules superimposed as a cover layer on a commercial single-mode planar glass waveguide. Transmission spectral holes and time-domain picosecond pulse propagation is studied by excitation via the evanescent part of the guided TE0-mode at liquid-helium temperature. We show that single-mode waveguide with SHB cover layer can act as integrated sub-gigahertz narrow-band filter.

INTRODUCTION

Spectral hole burning [1] is a versatile tool for high resolution spectroscopy [2] with numerous potential practical applications in optical storage and telecommunications technology. The possibility to change the optical parameters of the media such as absorption coefficient and correlated to it via dispersion relations index of refraction with sub-gigahertz selectivity in the frequency dimension is very attractive for constructing special photonic devices like narrow-band filters and modulators [3]. Most of the studies on SHB have been performed in the situation where the probing light is propagating in the SHB-active media. On the other hand, evanescent wave excitation or attenuated total reflection has been used for optical investigations of thin films on dielectric surfaces [4,5]. In this technique the total internal reflection of a light beam by the interface to a lower refractive index medium yields an exponentially decaying electromagnetic wave (evanescent wave) which penetrates a short distance into the medium where the wave itself does not propagate. By covering a planar waveguide with an absorbing material one obtains a continuous interaction of the evanescent wave with the sample over the whole length of the waveguide. An additional advantage of the waveguide geometry is that it provides a reproducible field distribution of the light wave which depends mostly on the fixed waveguide configuration and not on the alignment of the beams.

Our main interest in this paper is to combine the SHB technique with evanescent wave and integrated optical methods. We investigate the optical and spectroscopic properties of a device that consists of a commercial planar single-mode waveguide covered with a thin polymer film doped with SHB-active chromophore molecules at liquid-helium temperature.

EXPERIMENTAL DETAILS

We use commercial single-mode planar glass-waveguides (Artificial Sensing Instruments) consisting of a lower-refractive-index substrate glass ($n_S = 1.52$ at 633 nm) covered with a higher-refractive-index TiO_2-SiO_2 film (thickness d_F=160 nm, n_F~1.8) which serves as the light-guiding layer. The waveguide is provided with an embossed relief grating with a fringe period Λ=420 nm which is used to couple light to the TE0 mode.

The TiO_2-SiO_2 film is covered with a layer of polyvinylbutyral (n_C~1.7) doped with SHB-active chromophores. For this purpose the waveguide is dipped in a methylenchloride with dissolved PVB (25 g/l) and chromophore molecules. The concentration of the chromophore in the solution is about $5 \cdot 10^{-5}$mol/l. After evaporation of the solvent we obtain a uniform polymer layer of thickness l ~120 nm. The penetration depth $\Delta z_{F,C}$ of the guided mode in the cover material is on the order of 100-200 nm depending on the exact value of n_C.

In our SHB-experiments we use chlorin (2,3-dihydroporphyrin) molecules whose bulk- and thick-film hole-burning has been studied extensively [6]. The homogeneous line width of the $S_1 \leftarrow S_0$ transition at 633 nm is Γ_{hom}=160 MHz in PVB at 2K and the inhomogeneous broadening is Γ_{inh}~8 nm. In bulk polymer samples Debye-Waller factor (α_{DW} ~0.6 for PVB at T=2K) is high enough to be able to burn deep holes in the middle of the absorption band. The relatively low hole-burning yield Φ~10^{-4} prevents the burned holes from fast bleaching during readout.

To perform Stark experiments we vapor-deposit two CrCuAu-electrodes on the waveguide before covering it with the SHB-layer. This allows us to apply an external electric field in the y-direction. Fig.1 shows the schematic of the waveguide structure.

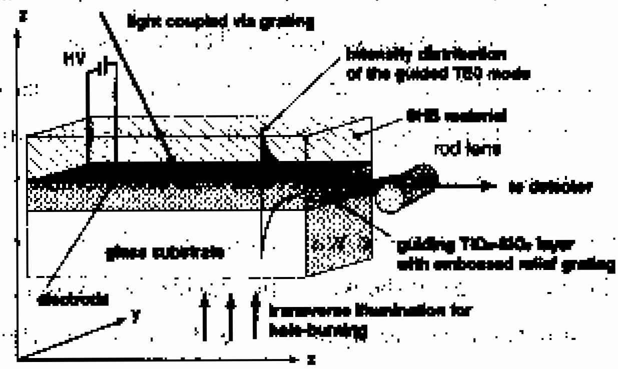

FIGURE 1. Construction of the waveguide.

The scheme of the experimental arrangement is shown in Fig. 2. As a light source we use either a synchronously pumped 76 MHz repetition rate picosecond dye laser (line width 0.4Å) or a CW diode laser (Philips CQL840D) with 110 MHz line width which is also tunable from 633 to 638 nm. The waveguide is fixed in a holder and is immersed in liquid helium at T=2K inside an optical cryostat. In the setup the laser beam is split into the probe beam (PB) and the burning beam (BB). The expanded burning beam illuminates the waveguide in a nearly perpendicular direction. The probe beam is directed through a pair of diffraction gratings and is then focussed to a 200 μm spot upon the embossed grating.

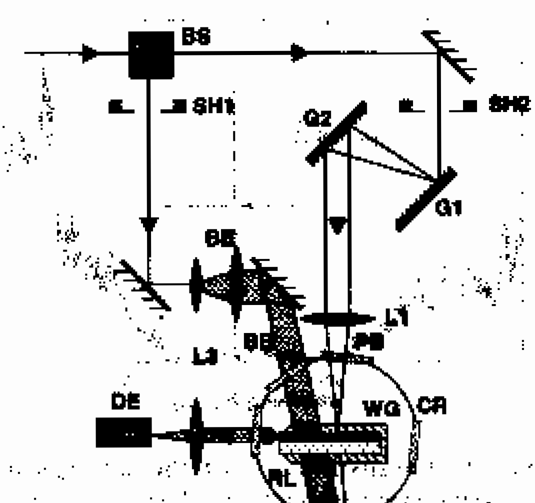

FIGURE 2. Experimental setup. BS-beamsplitter; G1,G2-diffraction gratings;BE-beam expander;L1, L3-lenses;WG-waveguide inside the cryostat;WG-waveguide; CR-optical cryostat; PB-probe beam;BB-burning beam;DE-detector;SH1,SH2-shutters to open and block the probe and the burning beams; RL-rod lens.

The optimum incoupling direction of the probe beam varies with the wavelength because of the angular dispersion of the waveguide grating. The dispersion of the external gratings and the focal length of the focussing lens are chosen to exactly compensate for the angular dispersion of the waveguide grating, so that nearly constant incoupling efficiency is maintained during the wavelength scan over several tens of nanometers.

The light transmitted through the waveguide is collimated by a rod lens (RL) positioned next to the output edge of the waveguide inside the cryostat. A further lens (L3) outside of the cryostat focuses the light on the detector. As the detector we use photomultiplier or, for time-resolved measurements, a 30-picosecond-resolution optical oscilloscope (Hamamatsu OOS-1).

RESULTS AND DISCUSSION

In the first experiment we investigate the possibility to burn spectral holes in the 120-nm thick layer and probe them via the evanescent wave absorption of the propagating mode. The waveguide is illuminated first with the dye laser at 635.1 nm transversely (burning beam) during 16 minutes with an intensity of 2 $mWcm^{-2}$. After that the shutter 1 is closed and shutter 2 of the probe beam is opened. About 0.5 µW of the dye laser probe beam couples to the TE0 mode. Fig. 3 shows the transmitted intensity of the guided mode when

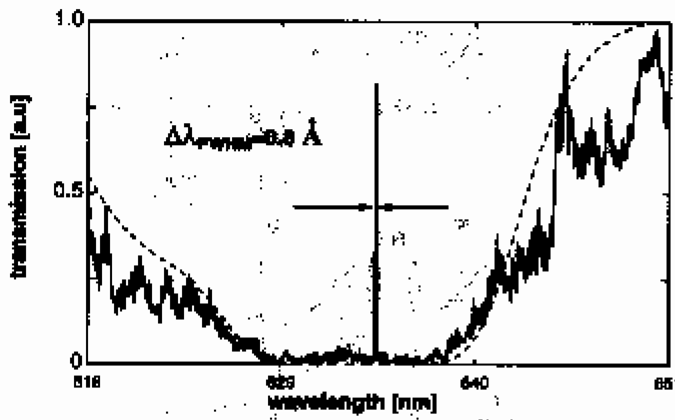

FIGURE 3. Spectral transmission of the waveguide. Solid line-experimentally measured transmission after the burning at wavelength 635 nm; dashed line-extrapolated transmission of a bulk sample with O.D.=3.5.

the dye laser wavelength is continuously scanned from 618 to 652 nm. The width of the transmission peak 0.8 Å is limited by the line width of the dye laser.

The contrast of the hole κ is defined as the ratio of the transmitted intensity at the center of the hole to the intensity detected at a nearby wavelength (in this case 1 Å away). The contrast is on the order of κ~ 64 and is in this experiment limited by collection of scattered light from the edges of the waveguide and from the lens in the cryostat. We can extrapolate the measured transmission curve with the transmission a bulk sample in the range 618 -652 nm (dotted line in Fig.3) and estimate the effective evanescent-wave absorption (the evanescent wave contains only 10-20% of the total intensity) to correspond to optical density O.D.=3.5. With this estimation and assuming no scattering the maximum possible contrast of the waveguide filter is κ_{max}~10^3.

As the next step we measure the spectral holes burned with the 110-MHz line width diode laser. We illuminate the waveguide structure in a transverse direction at 634.2 nm with an intensity of 33 μW/cm^2 for 11 minutes. We couple about 1 nW of the probe laser light to the TE0 mode and scan the laser frequency in the 10 GHz range around the former burning frequency. Fig.4 shows the transmission of the waveguide with the maximum at the original burning frequency. The hole width is $\Delta\nu_{FWHM}$= 570 MHz and after substraction

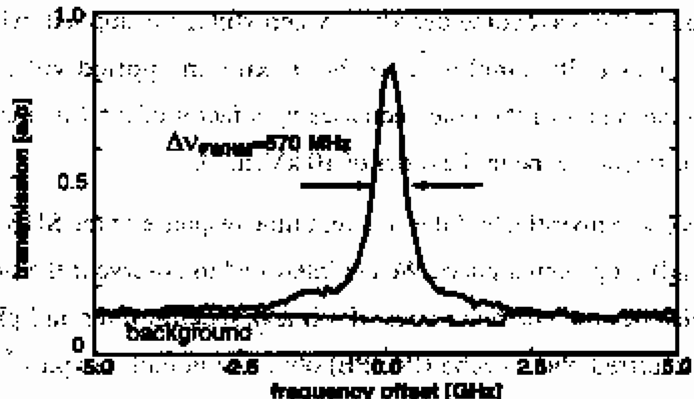

FIGURE 4. Waveguide spectral transmission after transverse illumination with 110-MHz-linewidth diode lase (black line). Gray line - backround signal level (mostly scattered light) measured before hole-burning.

the laser line width we find the homogeneous line width which corresponds within the experimental error to the value of conventional bulk samples Γ_{hom}= 160 MHz at T=2K.

In the further experiment we applied a variable voltage to the electrodes integrated into the waveguide structure and measured the transmitted intensity at the burning frequency of the diode laser. The electrodes (see Fig.1) have the form of metallic stripes of a thickness of 200 nm and width of 1.5 mm. The gap between the electrodes is 1.5 mm. The electric field is applied parallel to the surface of the waveguide and is therefore parallel to the polarization of a guided TE0 mode. The results are summarized in Fig. 5. We observe that

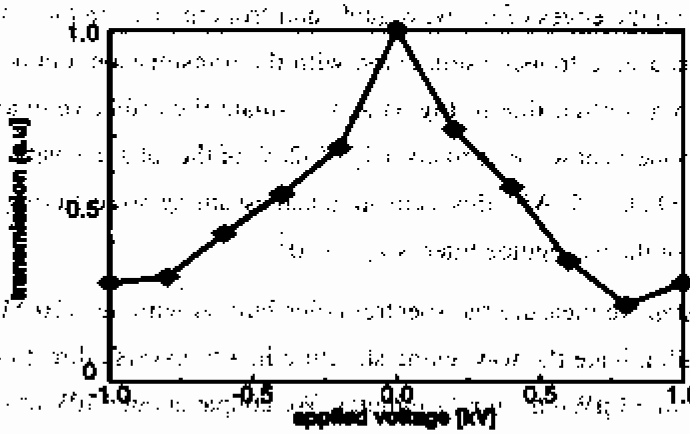

FIGURE 5. Transmission of the waveguide in dependence of the applied voltage. The spectral hole was burned and pobed at 634 nm with the diode laser.

the transmission of the waveguide decreases when voltage is applied, which indicates a similar behavior as bulk samples [7]. At the maximum applied voltage (±1kV) the transmission in the center of the hole decreases by a factor of 2.5 (the maximum applied electric field is estimated to be in the order of 10 kVcm^{-1}).

Our next task is to investigate if the coherent time response of the SHB-waveguide to a short (picosecond) propagating pulse. We are interested to observe if the time shape of the transmitted pulse has the characteristics of a linear spectral filter and photochemically accumulated stimulated photon echo (PASPE) observed in bulk samples [8]. As long as the absorption in the SHB-layer is small (SHB changes the absorption and correlated to it via dispersion relations index of refraction of the cover material), we can expect that the pulse propagation in this essentially spatially-inhomogeneous structure is not strongly disturbed by the hole-burning and we should be able to shape the guided pulses in time domain by tailoring the absorption profile of the cover SHB-layer in the same manner as with bulk samples.

To perform the experiment we change the setup by introducing in the burning beam of the picosecond dye laser a plane-mirror Fabry-Perot etalon. The burning light consists then of pulse trains with an exponentially decaying intensity generated by reflections between the two etalon mirrors placed d=19 mm apart. The time modulation means spectral modulation of the burning beam with a period 1/cd which is then stored in the SHB layer by transverse illumination with 4 mWcm^{-2} during 10 minutes. The read beam consisting of single ps pulses (repetition rate of 76 MHz) is coupled to the TE0 mode and the light transmitted through the waveguide is measured with the optical oscilloscope. Fig. 6 shows the measured time-resolved transmitted intensity where the transmitted read pulse at zero

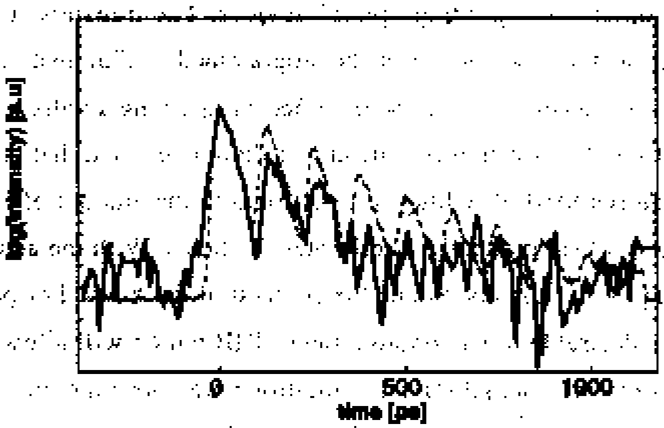

FIGURE 6. Time response of the waveguide after illuminating the SHB-layer coherent trains of picosecond pulses passed through a Fabry-Perot etalon (black line). Dotted line- direct time response of the Fabry-Perot etalon.

delay is followed by a series of PASPE pulses. Note that the spectral filtering in time-domain takes place via evanescent-wave interaction with the cover SHB-layer where only a fraction of the intensity penetrates. For potential narrow-band filtering applications [9] it is significant that the linear spectral filter approach describing PASPE still works in the present case where the media is essentially spatially inhomogeneous.

Nearby dielectric interfaces can influence the incoherent decay rates of optically excited molecules [10-12]. In a series of time-resolved fluorescence lifetime measurements of chlorin in PVB we observed that the molecules that are excited via the evanescent wave (and which are therefore close to the polymer-to-TiO_2-SiO_2-film interface) show on an average a 20% shorter lifetime that those excited by illumination in the bulk of the sample. Calculations based on a classical electric-dipole model in the vicinity of dielectric interfaces can quantitatively explained the observed effect of changing spontaneous emission probability [13].

In conclusion, the results presented above indicate that chlorin in a sub-wavelength-thickness film superimposed on planar glass waveguide has comparable hole-burning characteristics to that in a bulk sample. Under current experimental conditions the layered structure and the nearby dielectric interfaces appear to have little influence on the parameters such as contrast, width and stability in time of the spectral holes. The SHB-waveguide can be regarded as a miniature sub-gigahertz spectral filter which can be combined with other wave-guiding optical devices. The transmission of the filter in frequency domain and in time domain can be programmed by illumination with an external light source and the transmission can be modified by applying a voltage to the electrodes integrated directly in the waveguide structure. It should be noted that in our experiments the read beam causes SHB bleaching (proportional to the amount of light absorbed by chlorin molecules) which gradually deteriorates the holes. With the actual configuration about ten reading cycles already reduce the contrast of the holes. For potential practical applications it is desirable to use photon-gated SHB which will allow non-destructive operation. In various wavelength-division-multiplexing telecommunication applications the strongly preferred operating wavelength is 1.3 and 1.5 µm. It is important for the future technology to extend SHB into this wavelength region.

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