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-μm-thick polyimide film doped with chlorine molecules superimposed as a cover layer on a commercial single-mode polymer clad 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-nitrogen temperature. We show that single mode waveguides with SHB cover layers can act as integrated sub-gigahertz narrow-band filters.

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 spectral parameters of the modes such as absorption coefficients 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 this effect on dielectric surfaces \(^4\). 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 beam.

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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-bismuth temperature.

**EXPERIMENTAL DETAILS**

We use commercial single-mode planar glass-waveguides (Artificial Sensing Instruments) consisting of a lower-refractive-index substrate glass \( n_g = 1.52 \text{ at } 633 \text{ nm} \) covered with a higher-refractive-index TiO\(_2\)-SiO\(_2\) film (thickness \( d = 160 \text{ nm} \), \( n_g = 1.8 \)) which serves as the light-guiding layer. The waveguiding is provided with an embossed relief grating with a fringe period \( \Lambda = 420 \text{ nm} \) which is used to couple light to the TiO\(_2\) mode.

The TiO\(_2\)-SiO\(_2\) film is covered with a layer of polyvinylbutyral (n\(_g\) ≈ 1.7) doped with SHB-active chromophores. For this purpose the waveguide is dipped in a methylecchloroide with dissolved PVB (25 g/l) and chromophore molecules. The concentration of the chromophore in the solution is about 5·10\(^{-4}\) mol/l. After evaporation of the solvent we obtain a uniform polymer layer of thickness 1–20 nm. The penetration depth \( \delta_{\text{pen}} \) of the guided mode in the cover material is on the order of 100–200 nm depending on the exact value of \( n_g \).

In our SHB-experiments we use chlorin (2,3-dihydrophlorphyrin) molecules whose bulk- and thick-film hole-burning has been studied extensively. The homogeneous line width of the \( S_1 \rightarrow S_2 \) transition at 633 nm is \( \Gamma_{\text{hom}} \approx 160 \text{ MHz} \) in PVB at 2K and the inhomogeneous broadening is \( \Gamma_{\text{inh}} \approx 8 \text{ nm} \). In bulk polymer samples Debye-Waller factor \( \alpha_{\text{pol}} \approx 0.6 \) for PVB at 2K is high enough to be able to burn deep holes in the middle of the absorption band. The relatively low hole-burning yield \( \Phi \approx 10^{-4} \) prevents the burned holes from fast bleaching during detection.

To perform Stark experiments we vapor-deposit two Cr:Cu:Zn-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.
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 0.4 Å) or a CW diode laser (Phillips CQI 2400) with 110 MHz line width which is tunable from 633 to 638 nm. The waveguide is fixed in a holder and is immersed in liquid helium at 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 focused at a 200 cm spot upon the embossed grating.
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 focusing 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 scanned 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 P, for time-resolved measurements, a 30-picosecond-resolution optical oscilloscope (Hamamatsu OCS-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 15 minutes with an intensity of 2 μW/cm². 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 TEO mode. Fig. 3 shows the transmitted intensity of the guided mode when 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.

![Graph](image-url)
The central axis of the holes is defined as the axis 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 center is of the order of 10−64 and is thus expected limited by collection of scattered light from the edges of the waveguide and from the lens in the cryostat. We can extrapolate the measured transmittance curve with the transmittance 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 \( \Delta I_{\text{contrast}} \approx 10^3 \).

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 \( \mu \text{W/cm}^2 \) for 31 minutes. We couple about 1 \( \text{mW} \) of the probe laser light to the TE0 mode and scan the laser frequency in the 9 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 \( \Delta \nu_{\text{hole}} \approx 570 \text{ MHz} \) and after subtraction of the background intensity the transmission drops by \( \approx 5 \times 10^{-3} \) at 110 MHz.

![Waveguide spectral transmission after transverse illumination with 110-MHz line width diode laser (black line). Gray line: background signal level (mostly scattered light) measured before hole burning.](image)

**Figure 4.** Waveguide spectral transmission after transverse illumination with 110-MHz line width diode laser (black line). Gray line: background signal level (mostly scattered light) measured before hole burning.

In the further experiment we applied a variable voltage to the electrodes integrated into the waveguide structure and determined the transmitted intensity at the burning frequency of the diode laser. The electrodes (see Fig.5) have the form of metallic stripes of a thickness
of 200 mm and a 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 the guided THz mode. The results are summarized in Fig. 5. We observe that the transmission of the waveguide increases with increasing applied voltage. At the maximum applied voltage (±1 kV) 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 kV/cm). The transmission of the waveguide decreases when voltage is applied, which indicates a similar behavior as bulk samples. At the maximum applied voltage (±1 kV) 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 kV/cm).

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 characteristic of a linear frequency filter and photochemically accumulated stimulated photon echo (PCPFE) observed in bulk samples. As long as the absorption in the SHB-layer is small (SHB changes the absorption and correlated to it via dispersion relation index of refraction of the cover material), we can expect that the pulse propagation in this essentially spatially homogeneous 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 in bulk samples.

To perform the experiment we change the setup by introducing in the pulsed beam of the picosecond dye laser a plane mirror Fabry-Perot etalon. The resulting delay ensures that of pulse trains with an exponentially decaying intensity generated by fluctuations between
the two samples were placed 49 cm apart. The time modulation means spectral modulation of the boiling beam with a period 1/10 of which is then stored in the SHB layer by transverse illumination by 6 mW/cm² during 10 minutes. The read beam consisting of a single pulse (repetition rate of 26 MHz) is coupled to the TE0 mode and the light transmitted through the waveguide is measured with the optical monochromator. Fig. 6 shows the measured time-resolved transmitted intensity where the transmitted peak pulse as zero.

![Graph showing time response of the waveguide after illuminating the SHB-layer coherent trains of picosecond pulses passed through a Fabry-Perot etalon](image)

**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 is time-domain limited via transverse wave interaction with the SHB SHB-layer where only a fraction of the intensity penetrates. For potential narrow-band filtering applications it is significant that the linear spectral filter appropriate in this band PASPE still works in the present case where the beam is essentially spatially inhomogeneous.

Nearby dielectric interfaces can influence the incoherent decay rates of optically excited molecules. In a series of time-resolved fluorescence lifetime measurements of chlorin in PVK we observed that the molecules that are excited via the cytoplasmic wave (and which are therefore close to the polynucleic-acid-DNA film interface) show on an average a 20% shorter lifetime than those excited by illumination at the bulk of the sample. Calculations based on a classical electric dipole model in the vicinity of dielectric interfaces can quantitatively explain the observed effect of changing spontaneous emission probability.
In conclusion, the results presented above indicate that chlorine is a sub-wavelength-thickness film superimposed on planar glass waveguide has comparable hole-burning characteristics to that in a bulk sample. Under certain 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 chlorine molecules) which gradually depletes the holes. With the actual configuration about ten reading cycles already reduce the contrast of our holes. For potential practical applications it is desirable to use photorefractive 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.

REFERENCES