Waveguide narrowband optical filter using spectral hole burning

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Abstract. We have developed a new integrated narrowband optical filter, which consists of a planar waveguide coated with a thin polymer film containing molecules, which undergo persistent spectral hole burning at liquid helium temperature. We show that such a device performs as a miniature, reprogrammable narrowing optical filter, with a transmission bandwidth less than 1 GHz, in which a filter the frequency resolution is limited by the width of the homogeneous zero-phonon line of the chromophore molecules, and not by the geometrical dimensions of the device. Experimental measurements in the time domain using a photoelectric eye diode, and in the frequency domain using a single-mode diode laser, are presented.

Subject terms: Integrated optics; waveguide filter; spectral hole burning; photon arrays

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Minimal spectral filters, which can be integrated in optical waveguides, have a variety of potential applications for frequency-multiplexed optical data transmission and processing. Previously, integrated channel-dropping filters and tunable interferometers on planar waveguides have been demonstrated to provide a rejection bandwidth of about 1.0 to 1.0 A in the optical region, which corresponds to tens of gigahertz. However, to enable efficient use of a large number of different frequency channels, a rejection bandwidth of less than 1 GHz is desired. Unfortunately, the performance of passive devices based upon interference and diffraction of light has the tendency to deteriorate as the dimensions of the filter become smaller. This limits the practically achievable frequency selectivity and contrast of integrated optical filters. 1

An alternative approach to spectral filtering is to use the phenomena of spectral hole burning (SHB). 2 The special property of SHB materials is that they are able to transmit light at one frequency, while strongly absorbing light at all other neighboring frequencies. This wavelength selectivity occurs because at low temperatures the inhomogeneous absorption spectrum of molecules (or ions) in dielectric materials, such as polymers and crystals, comprises homogeneously zero-phonon lines (HPLs) that are much narrower than the overall absorption band of the ensemble of chromophores. If the chromophore molecules can be photochemically switched between two or more states with largely different absorption spectra, then it is possible to bleach out a narrow porting of the inhomogeneous absorption band by illumination with an intense monochromatic laser. The narrow dip or "hole" in the absorption spectrum can then be used as a narrowband filter for holographic storage and molecular computing, or for time domain holography and subpicosecond pulse shaping. 10

The zero-phonon line is especially narrow if the material is cryogenically cooled. At liquid helium temperatures, spectral holes narrower than 0.1–1 GHz are typical. Because the frequency selectivity is an intrinsic property of the material, the achievable contrast and the bandwidth of a filter do not critically depend upon the geometrical dimensions of the device. It is important, however, that the concentration of the SHB-active molecules be high enough to cause broadening of the ZPL due to energy migration between the chromophore molecules (see below).

In this paper we discuss the preparation of a miniature spectral filter that operates using a waveguide with a thin cover layer containing organic dye molecules. This cover layer is deposited on top of a commercial single-mode prism coupler waveguide in such a way that about 10% of the total energy of the guided light propagates in the cover material. Since the absorption in the cover material is substantial, a strong damping of the propagating mode occurs, and no light is transmitted through the waveguide. However, if a narrow hole is burned in the absorption spectrum of the cover SHB material, then at the frequency of the spectral hole the light is no longer strongly absorbed and the mode can propagate. 11

The experimental procedure consists of two steps. In the first step the absorption of the hole-burning layer is modified by illumination with light at a fixed wavelength. In the second step the transmission of the guided mode is measured by an
in- and outcoupled laser beam with tunable frequency. In the following, three experiments are described. The first experiment uses a synchronously pumped picosecond dye laser to demonstrate that spectral holes can be burned and detected in a waveguide configuration. The spectral width of the burned holes is limited by the spectral width of the laser, which is about a hundred times larger than the homogeneous ZPL linewidth. In the second experiment the time response of the waveguide structure is measured using the picosecond dye laser after a specific frequency profile has been burned into the spectrum of the waveguide. Using this technique, it is possible to estimate the homogeneous linewidth of the ZPL of the chromophore molecules, and to compare it with previously performed measurements in bulk samples. In the third experiment, holes with line-widths in the subgigahertz range are burned and detected with an cw diode laser.

The schematic structure of the combined SHB-waveguide is shown in Fig. 1. The light is guided predominantly in the 160-nm-thick layer of TiO₂-SiO₂ glass (refractive index \( n_r = 1.8 \)), which is deposited on top of a glass substrate of a lower refractive index \( n_r = 1.5254 \). The guiding layer also contains an embedded 2400-line/mm relief grating, which is used to couple light into the TE0 mode. The waveguide is covered with a thin layer of polymer (polyvinylalcohol, refractive index \( n_r = 1.7 \)) containing the SHB-active molecules which interact with the evanescent wave. This additional layer is prepared by dipping the waveguide in a methylenechlordiiodide solution containing 4x10⁻⁷ mol of chromin (2,3-dihydroporphoryl) molecules and 25 g/ml of polymer. A uniform layer of thickness about 120 nm is formed as the waveguide is slowly withdrawn from the solution and the solvent evaporates. The configuration of the waveguide structure allowed only the TE0 mode to propagate.

The scheme of the experiment is shown in Fig. 2. A tunable coherent light source was used either a synchronously pumped 780-nm-repetition-rate picosecond dye laser, which has a line width of 0.4 Å, or a narrowband cw diode laser from Philips (CQL490A), which can be controlled by temperature and current to emit laser light from 633 to 638 nm with a finesse of 110 MHz. The laser beam is split into the probe beam (PB) and the burning beam (BB), which can be opened and closed alternately by shutters 1 (SH1) and 2 (SH2). The waveguide is fixed in a holder and is immersed in liquid helium at \( T = 1.8 \) K inside an optical cryostat. The expanded burning beam illuminates the waveguide from a nearly perpendicular direction through one of the cryostat windows. The probe beam is directed through a pair of diffraction gratings and is then focused to a 200-µm spot on the embedded grating. When we scan the frequency of the laser to measure the transmission of the waveguide, the incoming direction of the probe beam has to vary 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 compensate exactly for the angular dispersion of the waveguide grating, so that constant transmission efficiency is maintained during the wavelength scan. The light transmitted through the waveguide is collimated by a small rod lens, which is positioned next to the output edge of the waveguide. A further lens (L3) outside of the cryostat focuses the transmitted light on the detector.

In the first experiment the laser is tuned to a wavelength of 633.14 nm, which is located at the center of the 90-nm-wide homogeneously broadened absorption band of the chromophore molecules. Shutter 2 is open, and the transmission beam is applied to illuminate the waveguide for about 15 minutes with an intensity of 2 mW/cm². After the exposure, shutter 2 is closed and shutter 1 is opened, coupling the probe beam into the TE0 mode of the waveguide. An estimated power of 0.5 µW is coupled into the TE0 mode. The laser wavelength is scanned, and the intensity of the transmitted light is recorded with a photomultiplier. The transmission of the wave-
guide measured after the exposure is shown in Fig. 3. As a result of the illumination with the beam, the sharp maximum with a total width of 0.5 A appears. When the frequency is tuned more than 1 A away from the transmission peak, virtually no transmitted light originating from the guided mode is observed. In fact, most of the light still reaching the detector is due to the probe beam scattered in the substrate glass and collected subsequently by the rod lens.

The extinction ratio of the filter, which we define as the ratio of the intensities measured at the centers of the holes to the intensities at a wavelength shifted by 1 A, is 10 fibr. However, since the intensity measured near the transmission peak is only due to scattered light collected by the rod lens in the cryostat, we extrapolate our measured transmission curve with the transmission of a bulk sample of chitosan molecules in PBS of optical density 3.5 (dashed line in Fig. 3); this extrapolation increases it to 10 fibr. Since many holes can be burned at any wavelength between 629 and 638 nm, one filter can have several transmission wavelength bands, as shown in Fig. 4. With the extrapolated optical density of our filter, we approximate the concentration of chitosan in the PBS matrix to be 10 fibr. It is known that the critical concentration of chitosan in polymer hosts for energy migration effects that result in broadening of the ZPL is above 10 fibr. The interaction length of the guided mode with the chitosan-doped polymer is 7 mm. With more concentrated polymer films on the waveguide, the actual size of our narrowband filter can be reduced to about 100 pm.

The width of the transmission line in Fig. 3 is exactly 2 times as large as the laser linewidth. Therefore, the question remains: What is the narrowest possible linewidth of the filter? In order to determine this we use the technique of photochemically accumulated stimulated photon echoes, as discussed in detail in Refs. 9 and 12, and measure the time decay of the echo signal. For this purpose we place a photomultiplier (PMT) in front of the filter, with a fiber spectral range of 0.25 cm-1, in the burning beam, as shown in Fig. 2. The light that is used for burning of the spectral holes consists of a sequence of narrow lines, separated by 0.26 cm-1. In the time-domain spectrum, the hole burning is carried out at the 76-MHz repetition rate of the laser, using exponentially decaying probe trains with a time spacing of 120 ps between the pulses (see Fig. 5). After a 10-min exposure with 4 mW/cm2 intensity, the burning beam is blocked and the transmission of a probe beam consisting of a single pulse traveling through the waveguide is measured. If the ZPLs of the impurity molecules are much narrower than 0.1 A, then the transmission of the waveguide should also contain many narrow holes with a 0.26 cm-1 spacing between them, and in the time domain the response should contain a train of echo pulses.

To measure the time dependence of the light emerging from the edge of the waveguide, we use a Hamamatsu OOS-91153 optical sampling oscilloscope with a time resolution of 30 ps. This solid line in Fig. 5 shows the measured time response. By comparing the decay of the echo signal...
pulse train with the decay of the original pulse train, we evaluate the upper limit of the width of the ZPL to be $10^{-20}$ to $50$ MHz. By comparing this value with the homogeneous linewidth of $1$ of the filter in bulk samples, we conclude that the partially restricted geometry of the polymer matrix prepared as a thin film does not significantly affect the interaction of the chromophore with photons, and that the narrower possible linewidth of the filter is in our case still well below $1$ GHz.

To support this statement we replaced our picosecond dye laser by a nanosecond cw dye laser with a laser linewidth of $100$ MHz. The dye laser can be scanned continuously without mode jumps over a range of about $20$ GHz. Since the singular dispersion of the waveguide grating in a frequency range of a few gigahertz can be neglected, we removed the gratings G2 and the lens L1 of the setup in Fig. 2. The principle of the experiment remains the same. We illuminate the waveguide transversely at a wavelength of $642.4$ nm with an intensity of $33$ mW/cm$^2$ for 1 min. After the exposure we block the burning beam and couple about 0.1 W to the TE$^2_0$ mode of the waveguide. Figure 6 shows the transmission of the waveguide device during a frequency scan of $10$ GHz. A sharp transmission maximum occurs at the burning frequency, with a linewidth of $500$ MHz and a contrast of 9.1 dB. The shape of the hole is approximately Lorentzian. The results shown in Fig. 6 were obtained with the same waveguide as in Fig. 3. However, the same contrast of the filter device was not obtained, possibly due to degradation of the chitin molecules. The burning fluence and the maximum intensity were significantly smaller in the experiments with the dye laser than with the picosecond dye laser, because of the narrower laser linewidth of the dye laser.

It should be noted in our experiments the real beam also causes a photothermal bleaching of the SHB materials in proportion to the amount of light absorbed by the chitin molecules, which gradually destroys the filter. With the picosecond dye-laser configuration we estimate that 75 reading cycles reduce the contrast from 18 to 15 dB. With the diode-laser configuration 10 reading cycles reduce the contrast from 9.1 to 7.9 dB. To achieve nondestructive readout, SHB materials that undergo two-color (photo-gated) hole burning should be used.

Spectral hole-burning devices work best at liquid nitrogen temperature, where one is able to compromise the performance, operating at higher temperatures is feasible with increased linewidth. New materials for high-temperature SHB are under investigation.\textsuperscript{13,14}

In conclusion, these experiments demonstrated that a planar waveguide covered with a thin polyimide film containing SHB material can change the transmission of the waveguide as a monochromatic narrowband spectral filter. Such a filter has a high contrast and good frequency resolution, not obtainable with currently used techniques. The width of the spectral interval over which the filter transmits light is limited by the width of the ZPL, and not by the geometrical dimensions of the device. In addition, we have shown that the linear coherent time response of the filter to photodarkening pulse corresponds to its transmission spectral profile.

For frequency multiplexed optical data transmission and processing, the planar waveguide operating at 1.5 $\mu$m is well suited to extend the capability of the device into this wavelength region as well. However, very little is known about SHB systems absorbing at wavelengths larger than 700 to 800 $\mu$m. Another interesting possibility is to place the SHB material between electrodes and use the Stark effect to switch the transmission with the electric field. Such experiments have been performed with bulk samples and recently thick films.\textsuperscript{15} In our case regeneration of minute electrodes onto the waveguide is conceivable. These new aspects are the subject of our further investigations.

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References

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