

Characterisation of Slow Light in a Waveguide Grating

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ABSTRACT

A grating was defined in a silicon nitride waveguide, using a combination of both conventional lithography and laser interference lithography. The structure was optically characterized in the 1520 – 1560 nm wavelength range by combining transmission measurements with the analysis of local out-of-plane scattered light, using a high-resolution infrared camera. From the measured power enhancement of the first Bloch-mode resonance above the long-wavelength band edge we estimated a $Q > 10^4$ and a group velocity of $< 0.1 c$.

Keywords: slow light measurement, waveguide grating, photonic crystal, resonance, Q -factor.

1. INTRODUCTION

Slowing down the speed of light by an appreciable amount compared to its value in vacuum may have several interesting applications and phenomena like large time delays [1] and field enhancement, e.g. for optical sensors [2], nonlinear optical devices [3], enhanced effective gain or low-threshold lasing [4]. Several mechanisms are known to provide a strongly reduced light velocity (“slow light”), like electromagnetically induced transparency [5], the coupled-resonator optical waveguide [6], and waveguides in photonic crystals [7].

In this work, we consider slow light that occurs for wavelengths near the photonic band edge of a waveguide grating, i.e. an optical channel waveguide with a finite grating section. The grating was etched into a shallow silicon nitride ridge waveguide, as illustrated by Fig. 1.

The transmission and reflection spectra of finite periodic structures in lossless media always show fringes near the stop-band edges. It is well known that the oscillations in the transfer function of a uniform grating are due to Fabry-Perot resonances of the grating Bloch modes [8]. We will show that relatively strong low-loss waveguide gratings can have a high quality factor for the first order resonances. For this we measured both the transmission through the grating using an end-fire set-up, and the light scattered out of the structure using an infrared-camera setup, see Fig. 2. The scattered light measurement is a tool for estimating the intensity enhancement factor and hence the group velocity in the grating region. Using this method we will make plausible that the group velocity at the photonic band edge of the grating is an order of magnitude smaller than the speed of light in vacuum.

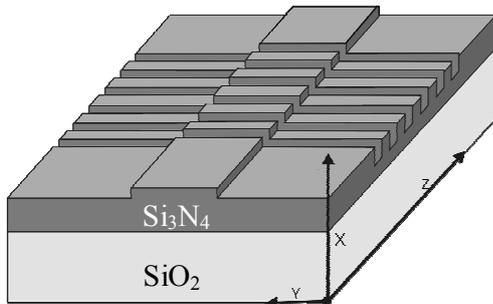


Figure 1. Schematic 3D view of a waveguide grating.

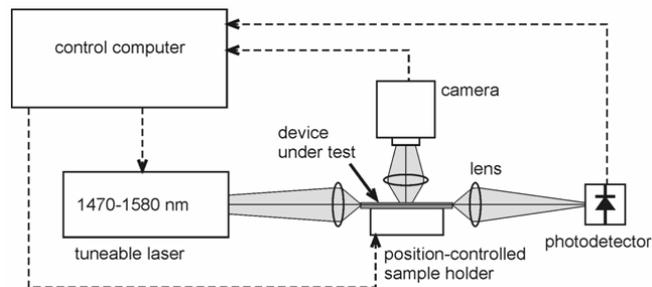


Figure 2. Measurement set-up.

2. EXPERIMENTAL

2.1 Fabrication

A 275 nm thick silicon nitride core layer (refractive index $n = 1.981$) was deposited by low-pressure chemical vapour deposition on top of an 8 μm thick silicon dioxide ($n = 1.445$) buffer layer on a silicon substrate. A shallow 5 nm high and 7 μm wide single-mode ridge waveguide was defined using conventional lithography and wet chemical buffered HF etching. An image-reversal type photoresist layer and a double exposure technique were used for defining the grating. First, a window was defined with a lithographic mask for the

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grating area, determining the length of the grating, and hence, the number of grating periods, which was chosen to be 500. Then, the grating pattern, having a 460 nm period and a 20% air filling factor, was defined with laser interference lithography [9], using a Lloyd's mirror set-up and a UV laser with 266 nm wavelength. After development of the resist pattern, the grating was etched to a depth of 60 nm with reactive ion etching using a CHF_3/O_2 plasma. Some samples were covered with a polymer cladding ($n \approx 1.5$).

2.2 Measurements

An automated measurement set-up (Fig. 2) was used for simultaneously recording a transmission spectrum and the wavelength-dependent patterns of scattered light of a waveguide grating. The camera records images of 320×240 pixels, and the optical magnification is set such that each pixel represents a $0.8 \mu\text{m} \times 0.8 \mu\text{m}$ chip area. Examples of measurement results are shown in Fig. 3. Spectral measurements (Fig. 3a & 3b) have been done on devices having a polymer cladding. Scattering intensity distributions (Fig. 3c) have been measured, however, for devices with an air cladding. Due to the difference in cladding index, the spectra of the air-clad device were down-shifted by approximately 70 nm compared to the polymer-clad devices. This scaling has been taken into account for locating the labels A-E in Figs. 3a & 3c.

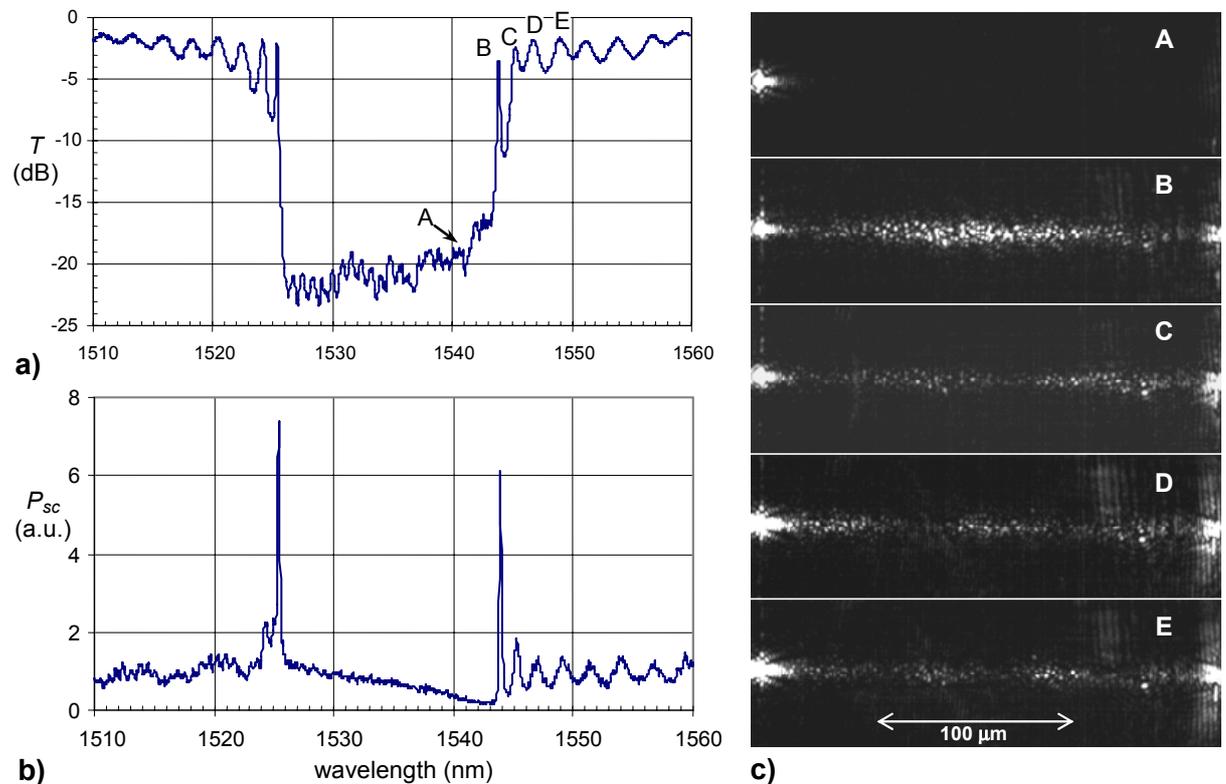


Figure 3. a) Measured transmission spectrum through waveguide grating. b) Measured spectrum of light scattered out of the waveguide grating (P_{sc} is scattered power). c) Camera images taken from the grating region. The bright spots to the left and right are the beginning and end, respectively, of the grating. Letters A-E correspond to the same letters in graph a), taking into account a scaling factor due to cladding differences as explained in the main text. Image A is taken for a wavelength in the stopband: scattered light is seen at the input of the grating, but not at its output. Image B shows a single intensity maximum, corresponding to the lowest-order resonance; C, D, and E show higher order resonances with 2, 3, and 4 intra-cavity maxima, respectively.

3. DISCUSSION

The measured data allow us to calculate the Q-factor of a grating resonance and the group velocity of the light in the grating. The narrow resonance peak near 1544 nm has a half power width of approximately 0.2 nm, both for the transmitted light (Fig. 3a) and for the scattered light (Fig. 3b). This leads to a Q-factor $Q = \lambda/\Delta\lambda \approx 8000$ for these polymer-clad waveguide gratings. Other measurements, on air-clad devices, showed a $Q \approx 14000$. We note that these large Q values are mainly due to the fact that near the band edge the modal propagation parameter is rapidly changing as a function of the wavelength, rather than to high modal reflectance at the transitions between non-grated and grating waveguide sections.

Although the camera images cannot, of course, resolve the sub-wavelength details of the field distribution in the grating area, they clearly show the envelope of the intensity distribution of the Fabry-Perot-like resonances of the Bloch modes in the grating. If we assume that the scattered intensity is proportional to the intensity in the waveguide grating, we can roughly estimate the power enhancement as the ratio of the peak scattered power and the average power scattered outside the stop band. This leads to an enhancement factor $\eta \approx 7$. The enhancement can be considered to be caused by a low group velocity, leading to a “compression” of the lightwave; assuming that the enhancement is approximately proportional to the modal group index it follows that $\eta = v_{g,u}/v_g = n_g/n_{g,u}$, where v_g and n_g are respectively the group velocity and the group index of the waveguide grating, and $v_{g,u}$ and $n_{g,u}$ the corresponding quantities in the undisturbed waveguide. With $n_{g,u} \approx 1.85$, we find that $n_g \approx 13$ and $v_g \approx 0.08 c$, where c is the speed of light in vacuum.

4. CONCLUSIONS

A silicon nitride waveguide grating has been fabricated using a combination of conventional mask-based lithography and laser interference lithography. It was characterised by both transmission and scattered light measurements. The scattered light measurements clearly showed several orders of Fabry-Perot-like resonances of the Bloch modes in the waveguide grating. The scattered light measurements also allowed estimating the intensity enhancement factor for the fundamental resonance mode, closest to the short-wavelength band edge, to be ~ 7 . This, in turn, lead to an estimated group velocity of $0.08 c$. This fundamental resonance mode was found to have a Q of ~ 8000 in polymer clad gratings and ~ 14000 in air clad ones.

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