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Nonlinear transmission properties of a deep-etched microstructured waveguide

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In this letter, we investigate the nonlinear transmission properties of a one-dimensional micro-structured AlGaAs waveguide with a defect in the middle of a deep-etched Bragg grating. The transmitted spectrum depends on the spectral position of the incident pulse spectrum with respect to the defect mode as well as the pulse intensity. These findings are very important for all optical switching applications and can be explained by the interplay between self-phase modulation of the incident 250 fs pulses in the waveguide and the filtering properties of the defect mode. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1765738]

Advanced communication systems are becoming increasingly limited in their performance by their electronic components. Hence, there is a a need to develop all-optical signal processing and routing elements which can operate at the bit speed. However, a prerequisite for all-optical data processing[1] is the development of effective all-optical switches which are the basis for any logic gate. There has been a great deal of interest in the use of photonic band gap (PBG) materials for this task,[2–7] since they promise efficient and yet compact devices. Optical switching in PBG materials can be achieved by the ultrafast Kerr effect.[5–7] The effective nonlinearity can be enhanced by a localized defect mode inside the PBG material, whose transmission properties can be tuned by the intensity dependence of the refractive index.

While this concept is very appealing from a theoretical point of view, there are many challenges to overcome. In order to keep the required switching intensities moderate, losses in the PBG structures have to be minimized to achieve a large quality factor (Q-factor) of the defect mode. This requirement poses high demands on the sample quality. Additionally, the spectral and temporal features of the pulses incident on the defect have to be matched to the properties of the defect mode in order to ensure high switching efficiency. Therefore, nonlinear pulse propagation effects have to be avoided in the device prior to the defect structure.

In this letter, we investigate the intensity dependent transmission properties of a *nonlinear* waveguide followed by a *linear* defect structure. The device consists of a AlGaAs waveguide, with a deep etched one-dimensional (1D) Bragg grating[8,9] containing a defect (see Fig. 1). We observe a pronounced spectral shift of the transmitted pulses even for moderate input intensities. These results are in agreement with the theoretical work of Perlin and Winful[10–12] on the transmission properties of a similar device based on fiber-technology. Its operation can be understood in the following way: A pulse propagating in the waveguide experiences self-phase modulation (SPM) which leads to a nonlinear phase shift $\Delta\phi_{NL}$.[13] Associated with the nonlinear phase shift there is an intensity dependent modification of the pulse spectrum. The spectrum broadens on both sides of the center wavelength and for high intensities ($\Delta\phi_{NL} > \pi$) develops a multi-peaked distribution (see Fig. 2). The defect-mode in the photonic band gap acts as a linear filter, transmitting only a part of the incident spectrum $I_{in}(\lambda)$. The transmitted spectrum $I_t(\lambda)$ is given by the product of $I_{in}(\lambda)$ and the transmissivity of the defect mode $T(\lambda)$. The shape of the transmitted spectrum depends critically on the intensity and center wave-

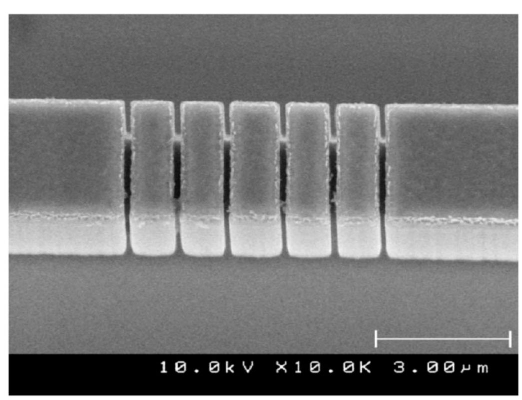

FIG. 1. Scanning electron micrograph image of the waveguide and Bragg grating with a defect in the middle.

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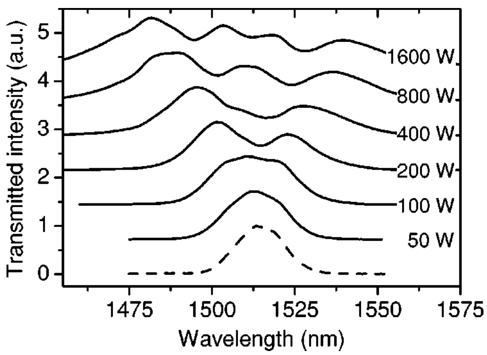

FIG. 2. Solid curves: normalized spectra of pulses transmitted through the unpatterned waveguide for different incident peak powers; these are shifted for clarity. Dashed curve: incident spectrum ($\lambda_0 = 1513$ nm).

length of the incident pulse, its spectral position relative to the defect mode as well as the quality factor of the defect mode. By carefully adjusting all parameters, the transmitted spectrum can be tuned both to longer, or shorter wavelengths with increasing incident intensity. Simulations show that in order to obtain pronounced spectral shifts, the spectral width of the defect mode must be comparable to the width of the edges of the multipeaked distribution. Therefore, a defect mode with a relatively low Q-factor is best suited for our experiments with femtosecond pulses.

Waveguides with a width of 2.5 μm, a length of 3 mm, and etch depth of 1.5 μm were fabricated by electron-beam lithography and reactive-ion etching on a (100) oriented GaAs substrate (see Fig. 1). The slab waveguide consists of a 1500-nm-thick 40% AlGaAs lower cladding, a 600-nm-thick 20% AlGaAs core, and a 200-nm-thick 40% AlGaAs upper cladding. AlGaAs was chosen because of its large $\chi^{(3)}$ nonlinearity with minimal nonlinear absorption in the 1.55 μm telecommunications window.[14] A Bragg grating was placed in the middle of the waveguide which is composed of five semiconductor elements with a width of 920 nm, separated by 200-nm-wide and 1.5-μm-deep air slots. The thickness of the center semiconductor element was increased to 1060 nm to form a defect. Due to the large dielectric contrast of the deep-etched structure a sizeable band gap can be achieved even with this short grating. The defect leads to a pronounced transmission peak in the photonic band gap centered at 1523 nm with a full width at half maximum of approximately 7 nm (see Fig. 3, solid line) which corresponds to a Q-factor of $Q = 217$. The patterned and unpatterned

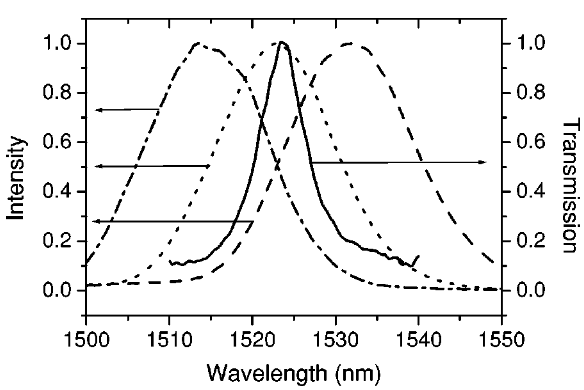

FIG. 3. Normalized spectra of incident pulses with $\lambda_0 = 1513$ nm (dash-dotted line), 1523 nm (dotted line), and 1533 nm (dashed line). Solid curve: normalized transmissivity of the defect mode.

waveguides were characterized with a diode laser by analyzing Fabry–Perot fringes. The linear losses of the unstructured waveguides are in the range of 5–6 dB/cm. The transmissivity at the center wavelength of the defect mode is smaller by a factor 20 or more, depending on the individual samples. These are typical values for deep-etched grating structures.

The nonlinear experiments were carried out with an optical parametric oscillator which produced 250 fs pulses tunable around 1500 nm with a repetition rate of 77 MHz. TE-polarized pulses were end-fire coupled to the waveguide with a 40$\times$ microscope objective and collected after transmission through the sample with a 20$\times$ microscope objective. In order to eliminate stray light, a pinhole was placed in the image plane of the second microscope objective. The spectra of the transmitted pulses were recorded using a monochromator and a Ge-photodetector.

For reference purposes the transmissivity properties of an unpatterned waveguide were measured and are illustrated in Fig. 2 for different peak incident powers (P) for an incident spectrum centered at $\lambda_0 = 1513$ nm. The spectral broadening of the transmitted pulses is a result of SPM. Compared to the initial spectrum, the rms spectral width[13] of the transmitted pulses for the highest peak power ($P = 1600$ W) is increased by as much as a factor of 3.2. Measurements, in which the peak of the incident spectrum was tuned to $\lambda_0 = 1523$ nm and $\lambda_0 = 1533$ nm, also yielded similar results (not shown here). In order to explain the asymmetry of the broadened spectra and to evaluate the different roles played by Kerr nonlinearity, two-photon absorption (TPA), and dispersion, we numerically studied the pulse evolution as it propagated along the waveguide. We used a beam propagation code including the Kerr nonlinearity, the first two dispersion coefficients[13] ($\partial^2\beta/\partial\omega^2$ and $\partial^3\beta/\partial\omega^3$, where β is the mode wave number) and the time-dependent TPA related change of the refractive index.[15] The blueshift and asymmetry of the spectrum are mainly due to the interplay between the TPA induced variation of refractive index, the slightly asymmetric shape[16] of the incident spectrum and chirp of the input pulses. Details of the complete calculation will be presented elsewhere.

We next consider the intensity dependent transmission properties of the structured waveguide. Since the defect structure is in the middle of the waveguide, the effect of SPM on the pulses entering the Bragg grating is smaller than that observed in the unstructured waveguide. $\Delta\phi_{NL}$ accumulated by the pulses critically depends on losses and dispersion. However, the spectral broadening of the pulses at the end of the unpatterned waveguide with half the incident power sets a lower bound, since the pulse intensity in the first half of the waveguide is larger than in the second part. Figure 3 shows the normalized spectra for incident pulses centered at $\lambda_0 = 1513$, 1523, and 1533 nm, and the normalized transmittivity of the structured waveguide. Figure 4 shows the corresponding spectra for different P and λ_0. For $\lambda_0 = 1513$ nm [Fig. 4(a)] and $P = 50$ W, the spectrum of the transmitted pulse peaks at 1522 nm. This is slightly below the transmission maximum of the defect mode since the incident spectral intensity decreases over the range of the transmission peak as shown in Fig. 3. However, as P increases, spectral broadening leads to an increase of the spectral intensity in the range of the transmission peak and consequently, the transmitted spectra shift to longer wavelengths. A shift as large as 3 nm was observed for P

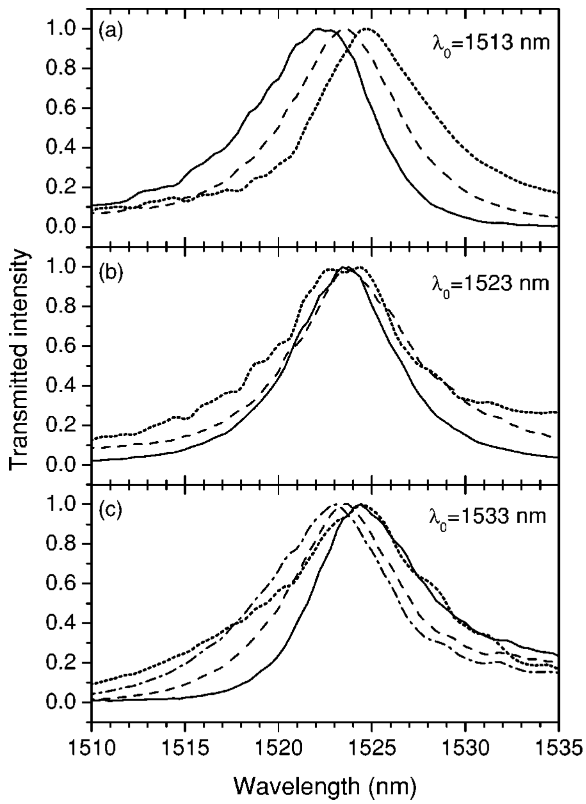

FIG. 4. Normalized spectra of pulses transmitted through the waveguide structure for different incident peak powers (50 W: solid line, 400 W: dashed line, 800 W: dash-dotted line, 1600 W: dotted line) and different center wavelength (a) λ_0=1513 nm, (b) 1523 nm, and (c) 1533 nm.

=1600 W. When the incident spectrum is tuned to λ_0 =1523 nm [Fig. 4(b)], which corresponds to the transmission peak of the defect, a qualitatively different behavior is observed: Instead of an intensity dependent shift, a broadening of the transmitted spectrum is observed. This broadening results from the fact that the spectral intensity on both edges of the transmission peak is simultaneously increased as SPM becomes more prominent. When the initial pulse spectrum is tuned to λ_0=1533 nm, Fig. 4(c), (i.e., 10 nm above the transmission peak of the defect mode), an increase from P =50 W to P=800 W shifts the transmitted spectra to shorter wavelengths. This blueshift is due to the change of the slope of the intensity in the spectral region of the transmission peak from positive to negative with increasing power. For the highest peak power (P=1600 W) the transmission peak is shifted back to higher wavelength. This oscillatory behavior of the peak position of the transmitted spectrum is expected since the slope of the intensity at the spectral position of the transmission peak is switching its sign again once a new peak of the SPM spectrum shifts in. Due to the asymmetry of the spectrum this situation occurs for lower peak power in the case of positive detuning than for negative detuning.

The current one-pulse scheme can easily be extended to two pulses.[11] In a co-propagating pump–probe configuration, the pump pulse will modify the spectrum of the probe pulse via cross-phase modulation.[13] Hence, by changing the pump power, the probe spectrum can be shifted in and out of resonance with the defect state representing the on and off states of a switch.

The results reported in this letter are also important for all-optical switching schemes which rely on changing the transmission of a localized state in a photonic crystal via non-linear optical effect.[5–7] Since intense pulses are required for this purpose, it is essential to assure that SPM in the waveguide leading to the defect can be neglected. Otherwise, the combination of SPM and the *linear* filter properties of the defect may easily be misinterpreted as a switching of the defect-mode itself.

In conclusion, we have experimentally investigated the nonlinear transmission properties of a 1D microstructured AlGaAs waveguide with femtosecond pulses. By carefully adjusting all parameters, the spectrum of the transmitted pulses can be tuned both to longer, or shorter wavelengths with increasing incident intensity. The spectral shift of the transmitted pulses results from the interplay between self-phase modulation in the waveguide and the filtering properties of the defect mode in the Bragg grating.

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