Broadband Bragg filter in microfabricated AlGaAs waveguides

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(Received 12 July 1995; accepted for publication 31 October 1995)

We report on the fabrication and characterization of broadband Bragg filters in microfabricated AlGaAs waveguides. Electron-beam lithography and chemically assisted ion-beam etching were used to fabricate first-order gratings with 250 nm period. Bragg filters with rejection bandwidth $\sim$15 nm and centered at $\sim$1.6 μm are demonstrated. © *1996 American Institute of Physics.* [S0003-6951(96)03602-3]

Broadband Bragg filters[1] can be useful for both linear and nonlinear optical applications. In the linear case, for example, they can be used as rejection filters for picosecond or femtosecond pulses, while in the nonlinear case they can be used for all-optical switching.[2,3] Recently, broadband Bragg filters fabricated in polymeric channel waveguides[4] and silica on silicon waveguides[5] have been reported with reflection bandwidths of 8 nm and 22 nm, respectively. In this letter we report the fabrication and characterization of broadband Bragg filters in microfabricated AlGaAs optical waveguides.

Bragg filters in general are characterized by a center wavelength and the bandwidth of the stop or rejection band. The center wavelength of the filter, λ_B, is given by $\lambda_B = 2n_{\mathrm{eff}}\Lambda$, where n_{eff} is the effective refractive index of the guided mode and Λ is the period of the Bragg gratings. In the preceding relation, the assumptions of first-order Bragg gratings and guided-mode propagation in the direction perpendicular to the gratings have been made. The bandwidth of the Bragg filter, $\Delta\nu$, is proportional to the effective refractive index modulation Δn_{eff} and can be shown[6] to be given approximately by $\Delta\nu/\nu \sim \Delta n_{\mathrm{eff}}/n_{\mathrm{eff}}$. This relation is strictly valid only when $\Delta n_{\mathrm{eff}} << n_{\mathrm{eff}}$, which is the case here. As can be seen from this last relation, broadband Bragg filters require a large Δn_{eff}, which can be obtained by fabricating relatively deep gratings in the guiding layer. For example, a Bragg filter with a 10 nm bandwidth at the wavelength of 1.6 μm requires about 0.6% refractive index modulation.

Figure 1 shows a diagram of the AlGaAs grating and waveguide structure used in this work. The grating structure was composed of first-order Bragg gratings with grating period of $\Lambda \sim 250$ nm and depth of 300 nm. The waveguide layer structure was comprised of 1 μm thick $Al_{0.23}Ga_{0.77}As$ guiding layer on top of a 3 μm thick $Al_{0.60}Ga_{0.40}As$ cladding layer grown on a semi-insulating GaAs substrate. Strongly-guided optical waveguides with a width of 1.5 μm were fabricated by etching down to the cladding layer. As shown, the Bragg filter structure is designed to have a bandwidth of $\sim$15 nm centered at a wavelength of 1.6 μm.

Fabrication of the AlGaAs Bragg filter waveguides was done using a two-step process in which the gratings were fabricated first and then the waveguides were patterned. The gratings were fabricated using electron-beam lithography and chemically-assisted ion-beam etching (CAIBE). The details of the procedure are as follows: first the AlGaAs wafer was coated with polymethylmethacrylate (PMMA) photoresist and then baked for 1 h at 170 °C. A 0.8 mm long grating pattern was then exposed using the JEOL JBX 5DIIU electron beam lithography system. The exposure conditions were 300 pA current, 50-keV accelerator potential, 80×80 μm field, and 11 mm working distance. The equivalent exposure dosage for the 250 nm gratings was 3.3 nC/cm. This set of conditions were chosen to give the optimum grating duty cycle of approximately 125 nm line and 125 nm space. The PMMA was then developed in a 1:3 solution of methylisobutylketone and isopropyl alcohol for 40 s. The resist image was transferred to the AlGaAs wafer by CAIBE using chlorine gas in conjunction with a 500 V argon ion beam. The PMMA was then stripped using a three step rinse of methylene chloride, acetone, and isopropyl alcohol, respectively. The grating depth was measured to be about 0.3 μm. After the grating fabrication, the sample was cleaned with a solution of hydrofluoric acid and water (volume ratio 1:10) for one minute. Afterwards, 1 cm long waveguides oriented per-

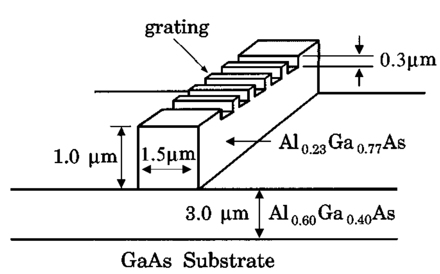

FIG. 1. AlGaAs Bragg filter waveguide structure.

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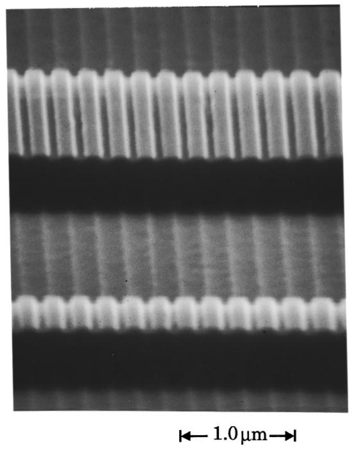

FIG. 2. SEM picture of the top-side views of the microfabricated strongly-guided AlGaAs Bragg filter waveguide.

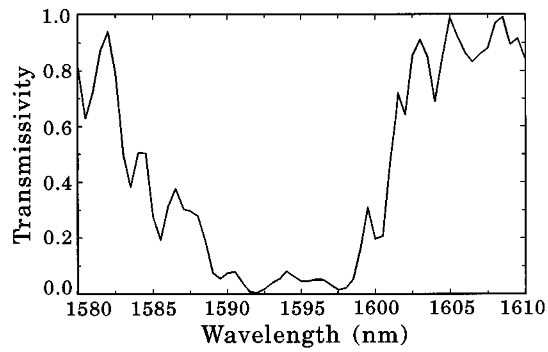

FIG. 4. Experimentally measured transmissivity spectrum of the AlGaAs Bragg filter with a FWHM bandwidth of about 15 nm.

pendicular to the gratings were patterned using conventional photolithography. The waveguide pattern was then etched down to the cladding layer using CAIBE, resulting in 1.5 μm wide strongly guided optical waveguides. Some of the waveguides were also patterned so that they did not overlap with the gratings, resulting in waveguides without Bragg filters. After the fabrication was completed the waveguides were cut to a length of 1 mm, leaving about 0.1 mm between the input of the waveguides and the beginning of the Bragg gratings. Figure 2 shows a SEM picture of the highly magnified top-side view of the strongly-guided AlGaAs waveguide with the etched gratings on top of the guiding layer.

The bandwidth of the Bragg filters was determined by transmission measurements. Figure 3 shows a schematic of the experimental setup. The laser source used was an additive pulse mode-locked (APM) color center laser (NaCl:OH) generating nearly transform-limited 150 fs pulses at 82 MHz repetition rate, with a full-width at half-maximum (FWHM) spectral bandwidth of 18.2 nm. An optical isolator was used to prevent unwanted feedback into the laser. The pulses were coupled in and out of the waveguide using 40× microscope objective lenses with a 0.6 numerical aperture. By careful alignment of the input beam, only the lowest order mode of the waveguide was excited. To minimize losses, both the front and back facets of the waveguide were antireflection coated. The transmitted pulse spectrum was measured using a computer-controlled Spex 270M scanning spectrometer

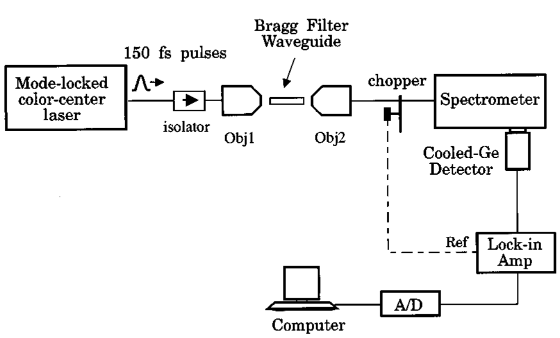

FIG. 3. Experimental setup to measure the bandwidth of the Bragg filter.

(maximum resolution of 0.3 nm) together with a liquid-nitrogen-cooled germanium detector and a lock-in amplifier. In our measurements the pulse center wavelength was tuned close to 1.6 μm using an intracavity birefringent plate, allowing the pulse spectral bandwidth to overlap with the Bragg filter rejection band. Since the femtosecond pulses had a spectral bandwidth slightly larger than that of the Bragg filter, the transmitted pulse spectrum had missing spectral components corresponding to the rejection band of the Bragg filter.

Figure 4 shows the transmissivity spectrum for the Bragg filter waveguide. The transmissivity spectrum was obtained by normalizing the transmitted pulse spectrum through a waveguide with gratings with the transmitted pulse spectrum through an identical waveguide without gratings. In all measurements the peak power coupled into the waveguide was kept sufficiently low to minimize the effects of self-phase modulation (SPM) on the transmitted pulse spectrum. As can be seen from the figure, the Bragg filter has a FWHM bandwidth of about 15 nm which is centered ~1594 nm and shows minimum transmissivity of about 2–5%. This minimum transmissivity is limited by leakage into higher order modes, which are not rejected by the Bragg filter. We also performed numerical calculations of the reflectivity for the Bragg filters. In this calculation, the Bragg filters were modeled using an efficient matrix method for complicated DFB laser structures.[7] Although this method applies only to plane-wave propagation in the grating structures, it can give a good estimate of the bandwidth of the Bragg filters. In this matrix method, the Bragg filter can be described by four complex 2×2 matrices representing field reflections at the grating interfaces and propagation through the grating region. The computation of the matrices requires the values for the effective refractive indices of the guided-mode in the grating region, which are calculated using the effective index method (EIM).[8] The refractive indices used in the EIM calculations at $\lambda = 1.6$ μm for the top, guiding, and cladding layers were $n_t = 1.0$, $n_g = 3.26214$, and $n_c = 3.08689$, respectively. The calculated effective refractive indices for the lowest order TE guided-mode in the grating region were $n_{e1} = 3.20697$ and $n_{e2} = 3.17234$, where n_{e1} and n_{e2} correspond to the 1 μm and 0.7 μm guiding layer thickness, respectively. The calculated reflectivity spectrum for

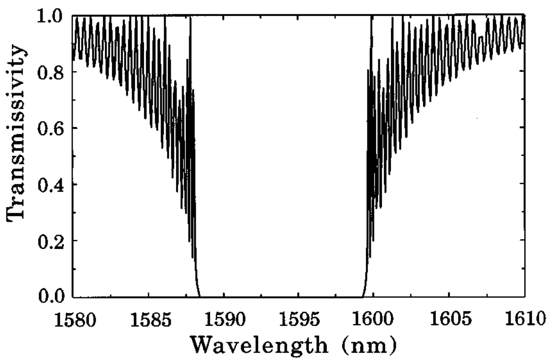

FIG. 5. Theoretically calculated transmissivity spectrum for a Bragg filter. The refractive indices used in the EIM calculations at $\lambda = 1.6$ μm for the top, guiding, and cladding layers were $n_t = 1.0$, $n_g = 3.26214$, and $n_c = 3.08689$, respectively.

the Bragg filter is presented as transmissivity in Fig. 5 so that a direct comparison can be made with the experimental data presented in Fig. 4. Our numerical calculations show that the rejection band is centered at 1595 nm and has a FWHM bandwidth of about 14.2 nm, in good qualitative agreement with the experimental measurement.

In summary, we report the fabrication procedure and characterization of broadband Bragg filters in microfabricated AlGaAs waveguides. These broadband Bragg filters were obtained by fabricating relatively deep gratings using electron-beam lithography and chemically assisted ion-beam etching. Transmission measurements show that the Bragg filters have a FWHM bandwidth of about 15 nm centered at $\lambda \sim 1.6$ μm. To the best of our knowledge, the Bragg filters reported here have the largest bandwidth in AlGaAs waveguides.

This work was supported by Advanced Research Project Agency under Contract No. F30602-92-C-0086-P03 and was performed in part at the National Nanofabrication Facility which is supported by the National Science Foundation under Grant ECS-9319005, Cornell University, and industrial affiliates.

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