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Physica E 13 (2002) 377–380

PHYSICA E

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Voltage-switchable Bragg reflector for planar optical waveguides

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Abstract

We present an experimental realization of a voltage-switchable in-plane Bragg reflector for planar waveguides. The device is based on the quantum confined Stark effect induced by an interdigitated gate in a multi-quantum well that is located in the core of the planar waveguide. Aspects of the sample preparation and room-temperature measurements are discussed.

PACS: 95 42.79.Fm; 85.60.Me

Keywords: Electro-optic devices; Bragg reflector; Optical waveguides

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The reflection and diffraction of light by a periodic modulation of the refractive index analogous to a Bragg reflection of X-rays by a crystal is a well-known effect. It is commonly used in planar waveguide devices such as distributed feedback lasers, vertical surface emitting lasers and surface acousto-optical modulators (see e.g. Ref. [1]). All these three device types have drawbacks: while in the first two cases the Bragg reflector cannot be switched, the reflection angle of a planar waveguide acousto-optic modulator is limited to small angles by the wavelength of the surface acoustic waves that cannot be reduced arbitrarily. Moreover, the area of the device is rather large due to the sending and receiving transducers and the HF electronics required to drive the transducers.

All these drawbacks could be overcome by the voltage-switchable Bragg reflector based on the quantum confined Stark effect (QCSE) that Govorov et al. proposed in Ref. [2]. This device could be useful for applications in optical communications for routing signals between different fiber inputs and outputs, and possibly also for novel semiconductor laser devices.

The device consists of a planar optical waveguide with a multiple quantum well (MQW) in its core. An interdigitated gate on the sample surface that is biased with respect to a back contact induces a periodically modulated static electric field in the waveguide core. The normal component of the electric field causes a periodic modulation of the refractive index in the quantum wells because of the QCSE. This index modulation induces photonic band gaps in the mode dispersion of the waveguide and thus acts as a Bragg reflector [2].

Here we present an experimental realization of this concept. Our sample is based on an $Al_xGa_{1-x}As$

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PII: S1386-9477(01)00562-8

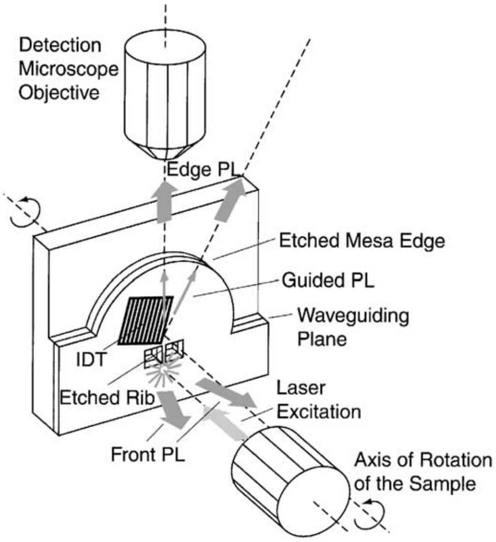

Fig. 1. Sketch of the sample and the experimental setup. The arrows in the sample plane mark the forward direction and the direction of the expected Bragg reflex, respectively.

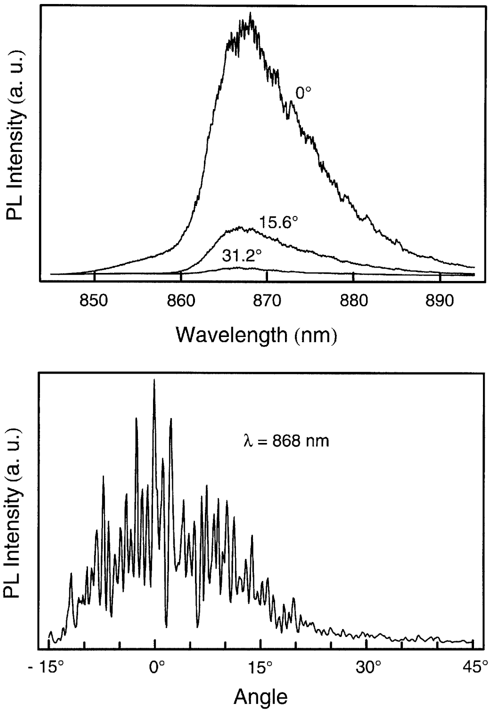

Fig. 2. Edge PL spectra for zero gate voltages. Top: PL intensity vs. wavelength for three different angles: forward (0°), parallel to the reflector front (15.6°), in the direction of the Bragg reflex (31.2°). Bottom: PL intensity vs. angle for the wavelength with the maximum PL intensity (868 nm).

heterostructure. The planar waveguide has a 200 nm thick core that contains twelve 10 nm wide GaAs quantum wells separated by 6 nm thick $Al_{0.3}Ga_{0.7}As$ barriers. The waveguide claddings consist of AlAs/GaAs superlattices corresponding to an average Al content of 0.4. The distance between surface and waveguide core is 43 nm and the Si-doped back contact is 500 nm below the waveguide core.

The interdigitated gate (IDT) is defined by e-beam lithography with a positive resist and gate deposition with subsequent lift-off. In our experiments, gates made from metals such as nickel–chromium or titanium strongly absorbed the light traveling in the waveguide even if the metal thickness was reduced to a minimum of 5 nm. Instead we chose RF sputtered indium tin oxide as material for both the bond pads and the gate fingers. We used a thickness of 120 nm for the bond pads and 8 nm for the fingers. Our lift-off technology currently limits the gate grating period to 250 nm and hence the period of the Bragg reflector to 500 nm. Since the wavelength of the TE_0 mode of our waveguide is approximately 250 nm we obtained a Bragg angle of approximately 15° and thus a deflection of the beam of 30°. By using a negative resist and an appropriate reactive ion or ion beam etching process, a further reduction of the grating period could be achieved, thus giving a larger Bragg angle.

Fig. 1 shows the design of the sample together with the experimental setup. In order to avoid a possible loss of the optical signal by total internal reflection at the cleaved sample edge we put the IDT for the Bragg reflector in the middle of a 1.5 μm high, 800 μm diameter semi-circular mesa with vertical edges. This mesa is defined by anisotropic reactive ion etching in $SiCl_4$ prior to the preparation of the gates.

Instead of using a tunable laser and coupling optics to feed light into the waveguide, we use the broad intrinsic room-temperature photoluminescence (PL) spectrum of the MQW as a built-in light source with wavelengths that are ideally matched to the optical properties of the waveguide [3]. The PL is excited with a 635 nm laser diode stabilized at 2 mW. The light traveling in all directions within the waveguide

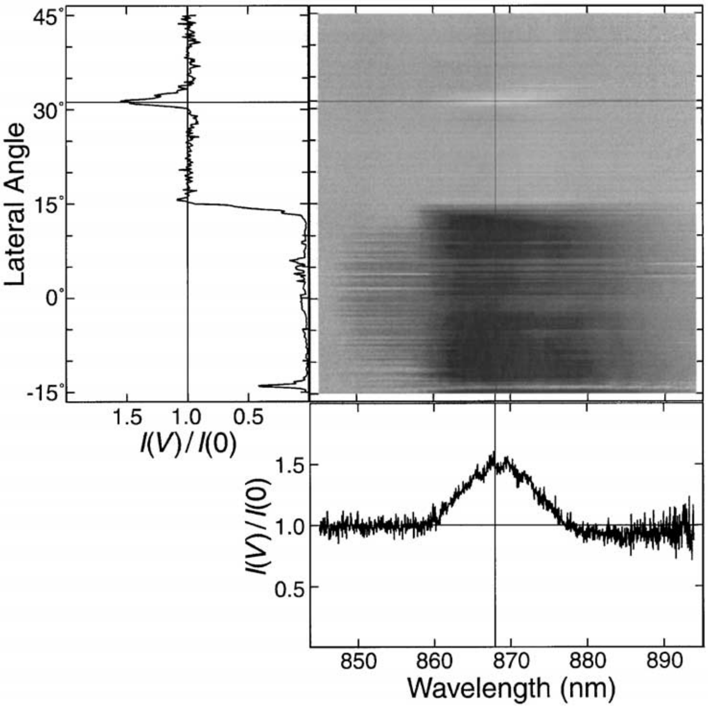

Fig. 3. Edge PL intensity for gate voltages $V_0 = -10.0$ V, $\Delta V = 6.25$ V divided by the PL intensity for zero gate voltage. The sections are at 868 nm and 31.2°, respectively.

is directed to the Bragg reflector area by a 10 μm wide etched rib defined together with the mesa. The PL light from the edge of the mesa is collected with a microscope objective and fed into an imaging spectrograph ($f = 300$ mm) allowing us to simultaneously record spectra from different heights of the mesa edge. The excitation laser is fixed relative to the sample and both can be rotated together around a surface normal through the center of the mesa which is also the intersection point of the straight light path from the rib and the front of the Bragg reflector area. Thus we can collect and analyze the edge PL from a wide angular range around the Bragg reflector. During the angular scans, we probed various combinations of negative gate voltages at every angle ($V_{1/2} = V_0 \pm \Delta V$). Positive gate voltages caused leakage currents from the back contact to the gates across the quantum wells, destructing the Bragg reflector effect permanently. We assume that the leakage currents induce permanent charges in the quantum wells that screen the gate voltage modulation.

Without gate voltages, we obtained in the angular direction for all wavelengths a bell-shaped PL pattern centered about the 0° forward direction (Fig. 2 bottom for $\lambda = 868$ nm). The noise-like structures in the PL intensity are caused by the roughness of the etched mesa edge. Fig. 2 top shows the edge PL spectra for three different angles (0°, 15.6° and 31.2°), ranging from about 860 to 890 nm with a maximum at about 868 nm.

In order to assess the effect of the Bragg reflector, we divided for every angle the PL spectra taken with non-zero gate voltages by the zero-voltage spectra. We found several distinct features (Fig. 3). In the angular region behind the Bragg reflector (−15° to 15° in Fig. 3) the PL was clearly suppressed. This is caused mostly by the QCSE redshift of the average quantum well absorption edge, but in part also by the Bragg reflector effect. In the angular region in front of the Bragg reflector ($> 15°$) the PL signal was essentially unchanged by the voltage applied to the gate electrodes. At 31.2°, a peak with an angular FHWM of approximately 2° was clearly visible. The angular position and the angular FWHM of this peak were independent of the applied gate voltages. The peak was weakly visible when the same voltage was applied to both gates ($\Delta V = 0$). This can be explained by the effect of a homogeneous gate, which causes a homogeneous index change at the front of the Bragg reflector area that acts like a dielectric mirror. With increasing voltage difference ΔV, the peak position shifted towards longer wavelengths and the peak height grew from 1.12 for $\Delta V = 0$ V to 1.52 for $\Delta V = 6.25$ V. This clearly demonstrates the dominance of the Bragg reflector reflection by the periodic index modulation over the reflection by the homogeneous index change that is also caused by the gate voltages. Comparing the data for $V = -10.0$ V, $\Delta V = 6.25$ V to the data for $V = 10.0$ V, $\Delta V = 0$ V, we found that the ratio of the increase in integrated PL intensity in the reflection peak ($31.2 \pm 2^\circ$, 868 ± 10 nm) to the decrease in integrated PL intensity in the forward direction ($0 \pm 2^\circ$, 868 ± 10 nm) is about 1%.

In conclusion, we have fabricated a voltage-switchable Bragg reflector for planar waveguides that is based on the QCSE-induced index modulation in a multi-quantum well under an interdigitated gate. Our room-temperature measurements show that incident light is indeed partly reflected in the direction of the Bragg angle, and that this reflection can be predominantly attributed to the Bragg reflection effect. In an optimized version, the voltage-switchable Bragg reflector could serve as a useful device for optoelectronic applications.

This work was supported by Bayerische Forschungsstiftung via the FOROPTO research programme.

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