concentration of the substrate was \( N_D \sim 10^{19} \text{cm}^{-3} \) (bulk resistivity \( \rho \sim 7.5 \Omega \cdot \text{cm} \)) and the sizes of the heavily doped \( n^+ \)-regions are \( 20 \times 150 \mu \text{m}^2 \) (on the mask). The distances of \( I_{C,2} \) and \( I_{EC1} \) were 120 and 20 \( \mu \text{m} \), respectively. The experiments were carried out at \( T = 300 \) and \( 77 \text{K} \) in the range of magnetic fields \( 1.2 \text{T} \leq B \leq 1.5 \text{T} \).

Fig. 2 Hall voltage \( V_H \) against emitter injection \( I_{EC1} \) for various bias currents \( I_{C,2} \) at fixed induction \( B = 1 \text{T} \).

Fig. 3 S-type characteristic \( I_{EC1}(V_{EC1}) \) for fixed current \( I_{C,2} \) at field \( B = 0 \).

The dependencies shown in Figs. 2 and 3 were also recorded at temperature \( T = 77 \text{K} \) on the same samples when their resistance was reduced several times by the increased carrier mobility. It was established that there was no negative resistance over the curve \( I_{EC1}(V_{EC1}) \) at current \( I_{C,2} > 0 \) and that the Hall voltage is practically uninfluenced by the emitter injection.

The obtained results are in complete agreement with the proposed model and are the first evidence in sensor electronics that the sensitivity of a Hall microsensor can be enhanced by minority carrier injection.

References

4 ROUMENIN, CII.: 'Solid state magnetic sensors' (Elsevier, Amsterdam, 1994)
mode is shifted upward (towards higher frequencies) by decreasing waveguide by increasing the radii of the air columns in the two rows that are adjacent to the middle slab. This results in the higher frequency of both modes, especially the odd mode. This effect is similar to the known property in the conventional dielectric slab waveguides that the dispersion diagram of each guiding mode is shifted upward (towards higher frequencies) by decreasing the slab thickness (or extending the area region).

Fig. 1 shows that there are two modes in the photonic bandgap (PBG). Calculation of the field patterns shows that these two modes have different symmetries (even and odd). This is not desirable for designing practical bends with good transmissivity in the PBG. One idea for obtaining singlemode propagation in the PBG is to reduce the thickness of the middle dielectric slab of the PBG waveguide by increasing the radii of the air columns in the two rows that are adjacent to the middle slab. This results in the absence of the photonic crystal modes at that frequency. Note that 0.254 < \omega(2\pi r) < 0.321 represents the absolute bandgap of the photonic crystal. The bandgap (frequency range with no mode present) at a specific value of \K_{d} can be wider than the absolute bandgap.

One interesting property of the even mode is the relatively flat nature of the corresponding mode at these values of \K_{d}.

\begin{align}
\text{Even} & \quad \text{Odd} \\
\text{Radii of all other air columns are equal to } r = 0.30a. \quad \text{Take the finite size of the waveguide in the third dimension (perpendicular to calculation plane), we assumed an effective permittivity or }
\end{align}

One interesting property of the even mode is the relatively flat nature of the corresponding mode at these values of \K_{d}. This is due to the coupling of the even mode to the other modes of the structure. This coupling is stronger for thinner slabs (or larger \ratio) due to reduced mode confinement in the middle slab. Therefore, the flat region of the even mode is extended to lower values of \K_{d} by increasing \ratio.

Note that the design of a bend using the proposed waveguide (with singlemode propagation in the PBG) is similar to that using a dielectric waveguide made by removing one row of air columns (the PBG waveguide with \ratio = 0.3). The design of the latter has been done by several research groups [1, 2]. The reason for the similarity of the design in two cases is that the positions of the centres of all air columns (including the ones adjacent to the middle slab) are the same in both cases. This is a main advantage of our design.

To summarise, we have presented a systematic way of designing dielectric-core photonic crystal waveguides with only one mode in the photonic bandgap. We showed that by redesigning the two rows of air columns that are adjacent to the middle slab, we can push the higher order modes out of the photonic bandgap.

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**References**

Narrow-band light emission in semiconductor-fibre asymmetric waveguide coupler

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A narrow-band, fibre-coupled light emitter based on the evanescent coupling between a semiconductor waveguide and a singlemode fibre is presented. The wavelength selectivity of the emission spectrum is caused by the index asymmetry between the two waveguides. A maximum linewidth of 1.5nm is obtained.

Introduction: Wavelength division multiplexed (WDM) communication systems require narrow-band, wavelength stabilised, and fibre-coupled light sources. Traditionally, such devices are obtained with the use of diffraction gratings (written either on the semiconductor source or the fibre) and butt-coupling to fibres. This method leads to high fabrication costs and high insertion losses. An asymmetric waveguide coupler, which is made up of a semiconductor waveguide evanescently coupled to a singlemode fibre, can provide solutions to these problems. In this Letter, we describe a narrow-band light emitter, implemented with a polished fibre half coupler and a semiconductor anti-resonant reflective optical waveguide (ARROW).

The fibre half coupler is made by epoxying a singlemode fibre into a curved groove in a glass substrate and then polishing both the substrate and the fibre cladding to within a few microns of the fibre core [1]. The ARROW consists of a core sandwiched between two distributed Bragg reflector (DBR) mirrors. The mirrors are doped to form a pin structure, and a quantum well is placed in the intrinsic region. When the ARROW is attached to the polished fibre half coupler, optical waves can be guided in its core by reflection from the n-doped DBR mirror on the one side, and a combination of reflection from the p-doped DBR mirror and total internal reflection from the fibre cladding on the other side. The device schematic is shown in Fig. 1. The mirrors help to support a propagating mode in the semiconductor that has a low enough effective index to phase-match to the fibre. The two waveguides have very different dispersion characteristics, therefore phase-matching occurs only at specific wavelengths. By forward biasing the pin diode, electrons and holes are injected into the intrinsic region and most of them recombine in the quantum well, creating photons. The photons are emitted into multiple modes, and only those that are phase-matched to the fibre mode are coupled into the fibre. Therefore, a narrow-band output from the fibre can be obtained.

Experiment: To demonstrate this device concept, a GaAs/AlGaAs ARROW was grown by molecular beam epitaxy (MBE) on an n+ GaAs substrate. The n-type and p-type DBR mirrors consist of 40 and 5 pairs of AlAs/Al0.33Ga0.67As quarter wave layers, respectively. The mirrors were optimised for maximum reflection at 25°C, which is the mode angle required for phase-matching to the singlemode fibre. The p-type mirror was designed to be partially reflective so that there is sufficient field overlap between the guided modes of the fibre and the ARROW. The core of the ARROW was made of an Al0.33Ga0.67As layer and a 75 Å GaAs quantum well. The quantum well was placed at the centre of the core where the intensity peak of the guided mode occurs.

Following MBE growth, the wafer was processed and cleaved into pieces for testing. During testing, the ARROW sample was mounted on a metal stage with conductive paste. A fibre half coupler (from Canadian Instrumentation and Research Ltd) with a polished interaction region of ~1mm in length was mounted on a x-y-z stage and positioned on top of the ARROW sample. The position of the fibre core was determined by launching light from a GaAs laser diode into the fibre half coupler and observing the scattered light with an infrared CCD camera. After aligning the fibre core to the ARROW, the two waveguides were brought into contact. Drops of index matching fluid, the index of refraction (1.485) of which was very close to the fibre cladding index (1.452), were applied at the interface to ensure good optical contact. The optical output from the fibre was observed using a spectrum analyser.

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