

Compact polarization converter in InP-based material

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Abstract: We present a polarization converter using one-dimensional grating principles. The device is based on slanted slots etched deeply into an InP/InGaAsP heterostructure. Almost complete polarization conversion, with a 14 dB extinction ratio, is observed for a device less than 2 μm long.

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1. Introduction

Controlling the polarization of light in a waveguide-based photonic circuit is a notoriously difficult task. Any incoming state of polarization decomposes into a transverse electric (TE) and transverse magnetic (TM) mode, both of which typically travel with different propagation constants. The obvious way to address this problem is to design polarization independent devices. These are indeed available, but they require tight tolerances to ensure that the two propagation constants are equal. As circuits become more densely integrated and waveguide cross-sections grow smaller, these tolerances are even harder to meet, so polarization independence is increasingly difficult to achieve. In the extreme, i.e. the nanophotonics context, with waveguide cross-sections of a few 100 nm, polarization independence is almost impossible to realize in practice. The solution then lies in the polarization diversity approach, whereby the incoming signal is separated according to polarization and the two are treated

independently from then on [1, 2]. Implementing polarization diversity requires a polarization splitter and a polarization rotator. While several concepts for polarization splitters are available [3-5], realizing an efficient polarization rotator, especially on a micrometre-size lengthscale, is a difficult task. Here, we demonstrate efficient polarization conversion on nanophotonic lengthscales ($< 2 \mu\text{m}$) with a device based on one-dimensional grating concepts.

The device operates similar to a half-waveplate well-known from bulk optics. The key difficulty in realizing such a waveplate in a waveguide geometry is to create an optical axis that is rotated at 45° to the two polarizations of interest. Previous approaches have used a slanted-rib geometry whereby a rib waveguide was fabricated with one straight and one angled sidewall [6]. Here, we demonstrate an approach based on one-dimensional photonic crystals, inspired by Cai *et al.* [7] that relies on angled slots etched into the waveguide, with light propagating along the slots. Light of a given input polarization is decomposed into two components, one component being polarized along the slots and the other perpendicular to them. Due to form birefringence [8], the component with its polarization along the slots experiences a lower effective refractive index and therefore advances on the other. The input polarization rotates by 90° for a phase shift of π between the two modes. The high refractive index contrast in the semiconductor-air system we use ensures a high form birefringence (Δn of ≈ 0.5) resulting in a conversion length of less than $2 \mu\text{m}$.

2. Fabrication

The InGaAsP heterostructure (grown by *Alcatel*) used in the experiments consists of a $0.3\text{-}\mu\text{m}$ -thick InP top cladding layer and a $0.522 \mu\text{m}$ InGaAsP (Q 1.22) core layer, followed by InP lower cladding (Fig. 1). A set of 230-nm slots with a 650 nm period was written using electron-beam lithography (Raith Elphy Plus/Leo 1530) in a 200 nm thick layer of polymethylmethacrylate. The pattern was then transferred into a hard silica mask using reactive ion etching with fluorine chemistry (CHF_3). The silica mask was created using commercially available hydrogen silsesquioxane (HSQ) resist that was simply applied through spin coating. Baking this resist at high temperatures ($\sim 400^\circ\text{C}$) partially transforms the film into silica [9].

The deep etching of the slots was performed using a high voltage low current chemically assisted ion beam etching (CAIBE) regime at a temperature of $\sim 200^\circ\text{C}$ [10]. The sample was mounted on a slanted holder in order to etch the slots at the desired angle of 45 degrees. An example of the etched slanted slots is presented in Fig. 1.

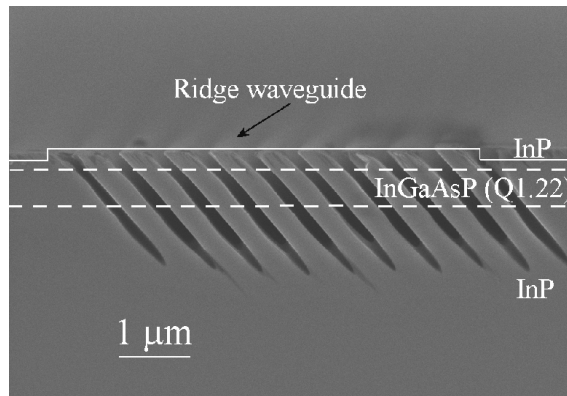


Fig. 1. Cross-section of 230-nm wide slots etched at 45° into an InP/InGaAsP waveguide heterostructure. The sample was etched using a beam voltage of 1450 V, a beam current of 17 mA, 2 sccm of Cl_2 and 10 sccm of Ar. The bold white line schematically represents the cross-section of the ridge waveguide (defined by photolithography and shallow etching) into which the slots are etched.

The access input/output ridge waveguides (5 μm wide) were defined using photolithography. The shallow etching (~ 100 nm) necessary for operation in a single mode was realized using a second stage of CAIBE etching with the photoresist as the protective mask (Fig. 2). Finally, the sample was cleaved into die of approx. 1mm length.

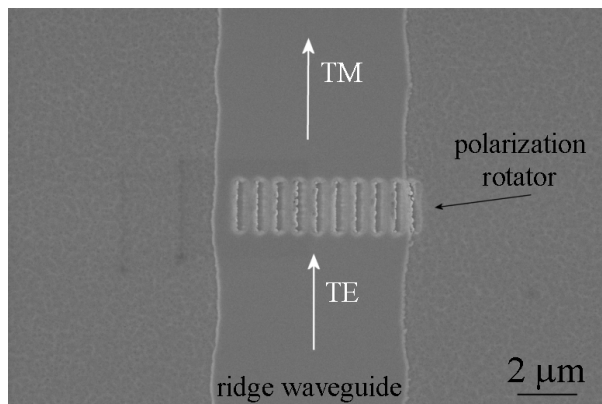


Fig. 2. SEM image of the top view of a finished device illustrating the input/output shallow etched 5- μm wide ridge waveguides and a 1.5- μm long polarization converter consisting of deeply etched slanted slots. The slight misalignment between the slots and the waveguide is caused by the limited alignment accuracy of our photolithographic process.

3. Experiment and theory

A tunable laser operating between 1250-1365 nm was used to launch light into the device via a microscope objective. The polarization of the incoming light was set to either TE or TM, with an analyzer on the output side.

Devices with polarization converter sections varying from 0 μm (blank waveguide) to 4 μm in length were tested. Figure 3 presents the experimental dependence of the output power in TE polarization on the length of the polarization converter for both TE and TM incoming polarizations. As one can see from Fig. 3, the optimal length at which the output polarization was rotated by $\sim 95\%$ with respect to the incoming polarization is approximately 1.6 μm for this type of slanted grating. At a length of about 3.2 μm , the incoming polarization was rotated through 180 degrees returning the output light to the initial polarization.

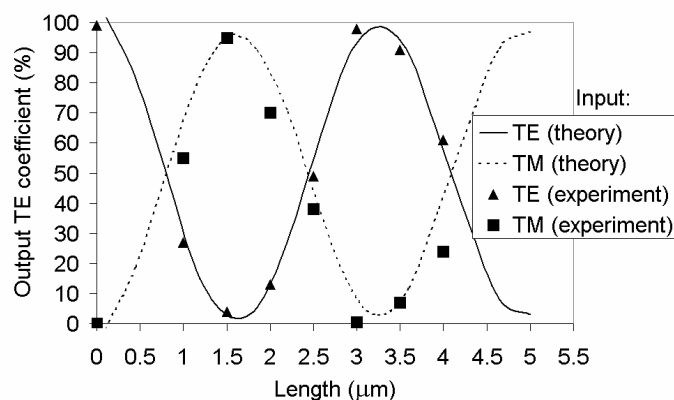


Fig. 3. TE fraction of the output light vs the length of the polarization converter for both TE and TM input polarizations. The dots are the experimental data and the lines are modeled. The polarization rotator consisted of 270 nm wide air slots (with a 650 nm period) etched at an angle of 45 degrees.

A good agreement between the simulation performed with a full 3D FDTD and the experimental results can be seen in Fig. 3. The experimental TE coefficient data points were defined as the fraction of the total out-put power in the TE polarization and the theoretical value was defined as the real Poynting vector flux due to one polarization as normalized to the total Poynting vector flux. Thus, this coefficient is loss independent. One can see that the TE coefficient in Fig. 3 exceeds the 0-100% bounds- this problem only arises for an almost zero-length device. In this case, the FDTD can give numerically inaccurate results since the zero-length point corresponds to simply the interface between the input waveguide and the polarization converter. The mode is not formed yet and higher order modes or radiation modes can give significant contributions.

The simulation was performed assuming a slot width of 270 nm. This width is slightly larger than the experimentally determined width of 230 nm, although there is some experimental error due to the variation of slot width with etch depth. In the following, we therefore refer to an “effective” width of 270 nm for the air slots.

Figure 4 depicts the absolute normalized output power vs. analyzer angle for a blank waveguide and a waveguide containing a 1.5 μm long polarization converter (the incoming light was TE polarized for both cases). As can be seen from the figure, the maximum output power (100 %) is in TE polarization (0 degrees) for a blank waveguide. At the same time, 96 % of the output light is in TM polarization (~ 90 degrees) with only 4 % remaining in TE polarization for the waveguide with the 1.5 μm long polarization converter. This represents an extinction ratio of 14 dB.

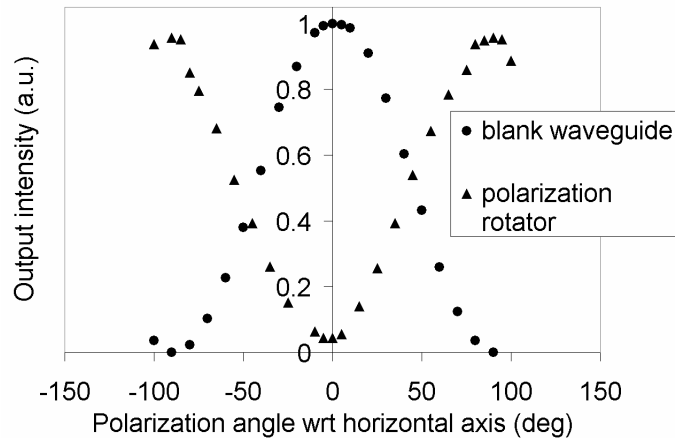


Fig. 4. Output power vs. polarization angle for TE incoming light.

For a given width of air slots, the optimal performance of the device strongly depends on the air/semiconductor width ratio (this ratio is $\sim 1:1.5$ in the case depicted in Fig. 3). Indeed, if the semiconductor width increases, the grating tends to resemble a uniform slab waveguide with tilted walls and the form birefringence is much reduced. The structure then approximates the type of asymmetric waveguide studied previously [6]. Increasing the semiconductor width for fixed air slots reduces the form birefringence due to a decreased difference between the effective indices of the two orthogonal eigenmodes. This leads to a longer beat length as illustrated in Fig. 5. For a fixed width of air-slots, there is an almost cubic dependence of the beat length on the air/semiconductor ratio. In the other limit, for very small semiconductor width, the form birefringence increases, but the interface reflectivity also goes up due to increased mismatch with the input waveguide. Device fabrication also becomes technologically more demanding for large air/semiconductor ratios. This simulated trend is

supported by experimental evidence. A device with a 1:4 air/semiconductor ratio and the other parameters unchanged (air slots=270 nm effective width, semiconductor width=1080 nm) showed an optimal length of 30 μm (Fig. 5).

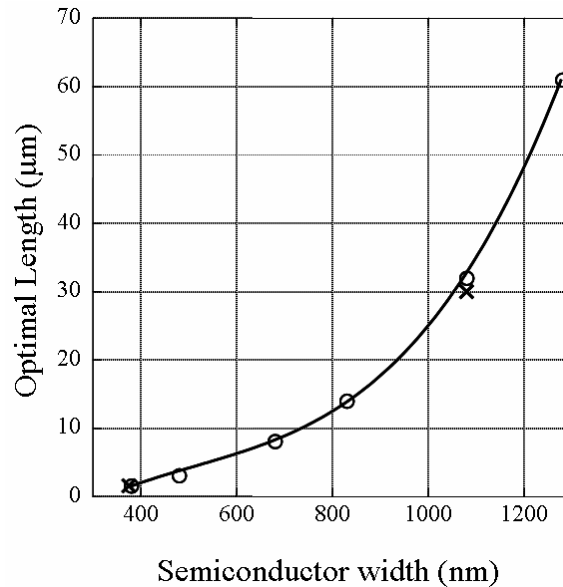


Fig. 5. Simulated dependence of the beat length on the width of the semiconductor section for a 270 nm width of the air slots. Filled dots: simulated values. Solid line: guide to the eye, corresponding to a cubic fit. Crosses: experimental values.

In terms of transmitted power, we currently observe a loss of 3 dB (compared to a ridge waveguide without polarization converter). The corresponding theoretically predicted losses are around 1.3 dB for deep ($\sim 2 \mu\text{m}$) slanted slots with perfectly parallel sidewalls and 3 dB for similar slots with conical walls. Thus the main source of the loss is considered to lie in the imperfect, irregular or conical shape of the holes as well as insufficiently deep etching [11]. Both of these problems result in undesirable out-of-the plane scattering. These issues, however, can be minimized by optimizing the etching regime and achieving deeper, more parallel slots. As technology continuously improves, better slots should be achievable in the near future. The remaining loss of 1.3 dB is due to the abrupt interface between the slotted and unslotted sections. Further improvements in the interface design, such as more adiabatic transitions, will reduce these losses to acceptable levels.

With respect to bandwidth, it is worth noting that the experiments were performed at several different wavelengths in the 1290 to 1330 nm range, with no compromise in performance; this clearly indicates broadband operation, which is also supported by the predicted wavelength window of 200 nm (Fig. 6).

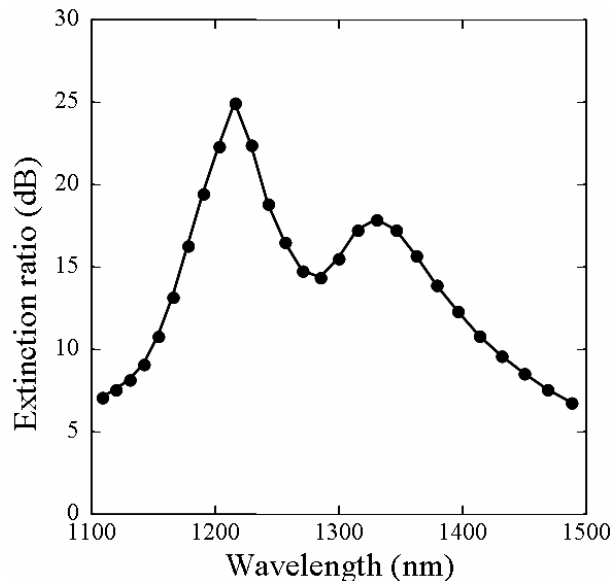


Fig. 6. Simulated wavelength dependence of the TE/TM extinction ratio at the output of the same device as in Figs. 1 and 2 for a TM polarized input mode. The simulated TE/TM extinction ratio is larger than 15 dB over the range 1170 nm to 1370 nm.

4. Conclusions

Ultra-small (1.5 μm long) polarization converters with 14 dB extinction ratio based on one-dimensional slanted gratings were achieved experimentally in a InP/InGaAsP waveguide heterostructure. Narrow slots (~ 270 nm) were deeply etched into the waveguide at an angle of 45 degrees with light propagating along the slots. The design forces the input mode to decompose into two orthogonally polarized components, one component being polarized along the slots and the other perpendicular to them. The short conversion length is due to the high form birefringence ($\Delta n \approx 0.5$) of the structure.

The realization of such compact polarization converters in InP waveguide heterostructures makes them very attractive for integration with photonic integrated circuits. These devices constitute critical components for polarization diversity circuits on a very short lengthscale.