# Anomalous light propagation and diffraction control in waveguide arrays

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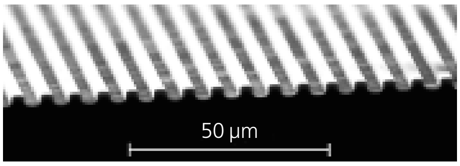

Fig. 1:
Polymer waveguide array of 75 single mode waveguides (before applying the polymer cladding).

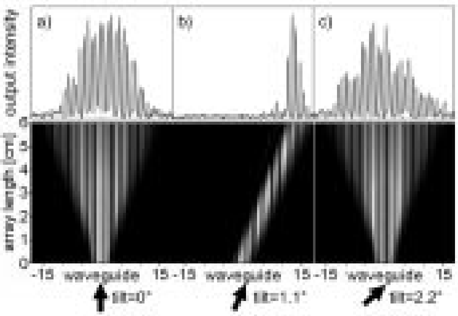

Fig. 2:
Measured output intensity profile and simulated propagation for a Gaussian excitation with several input tilts.

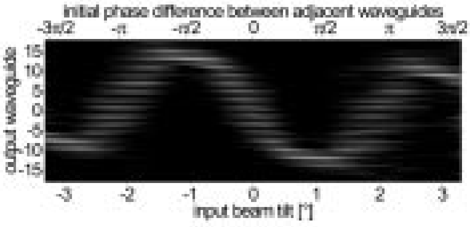

Fig. 3:
Measured output intensity profiles vs. tilt of a Gaussian input beam.

## Introduction

Our understanding of light propagation primarily derives from isotropic media. The law of refraction predicts that the tilt of a beam traversing an interface between two media will monotonously grow with the angle of incidence. The law of diffraction predicts beam spreading being completely determined by the ratio of wavelength and width, which is only slightly affected by the refractive index and independent of the tilt. The reason for this behavior is the rotational symmetry of the isotropic medium. If this symmetry gets lost, as e.g. in a stratified medium (Bragg mirror) or a discrete system (array of waveguides), these canonical laws of refraction and diffraction cease to hold. The mathematical background is the relation between the transverse (k) and the longitudinal wavenumber component (b) of the wave vector, which constitutes the diffraction relation analogously to the dispersion relation in the temporal domain. In two-dimensional isotropic media we have $\beta = \sqrt{n^2 - \kappa^2}$ whereas in the general case this is a more complex function $\beta = f(\kappa)$. We demonstrated anomalies in light refraction and diffraction in evanescently coupled waveguide arrays ('discrete' refraction and diffraction) /1-3/.

## Experiments

The experiments were performed on homogeneous arrays of 75 waveguides in an inorganic-organic polymer ($n_{co}$=1.554) on thermally oxidized silicon wafers ($n_{sub}$=1.457) with polymer cladding ($n_{cl}$=1.550) (Fig. 1). The 6 cm long samples were fabricated by UV-lithography on 4" wafers. Each waveguide has a cross-section of 3.5 x 3.5 µm$^2$ and provided low loss single mode waveguiding (< 0.5 dB/cm) at $\lambda$ = 633 nm. The uniform separation of adjacent guides was 8.5 µm to achieve efficient evanescent coupling. A HeNe laser beam was shaped with respect to width and tilt using a telescope and coupled into the array via the entrance-facet with a microscope objective. The light emitted from the end-facet is detected by a camera. Because light propagation along the array cannot be monitored, it is visualized by numerical simulations instead.

In Fig. 2 the most spectacular consequences of anomalous refraction and diffraction are displayed. In Figs. 2a and 2c measurements and modeling show that, like in an isotropic medium, diffraction of a Gaussian input beam compares for two different input angles. But refraction is anomalous, i.e., the 2.2° tilted beam exits the array at the same location as the untilted beam. On the contrary, Fig. 2 b is an example for normal refraction but anomalous diffraction because the beam, which is tilted by 1.1°, crosses the array diffractionless.

To systematically study these anomalies we continuously varied the angle of incidence of the beam. This was achieved by shifting the laser beam off-axis in front of the in-coupling microscope objective, resulting in a stationary focus with a tilt proportional to the off-axis translation. We monitored the field at the output facet, the shift of which is proportional to the angle of propagation inside the array. For an isotropic system this shift would monotonously grow with the tilt and the beam width at the exit face would be invariant for changing tilt. In fact, for small angles the transverse motion of the field in the array was found to be proportional to the initial tilt. But for growing angles this shift saturated and even reduced resulting in an oscillatory dependence (see Fig. 3). Evidently, two features of light propagation can be recognized, there is a maximum angle of propagation that cannot be exceeded and the width (strength of diffraction) varies with the input angle.

## Theory

The theoretical analysis is based on a coupled mode theory. This means that the incident field is mapped onto a finite number of mode amplitudes of the individual guides. Therefore, phase differences between adjacent guides of multiples of 2π will have no effect on the field evolution. Apart from a reduced incoupling efficiency, the response of the array on initial tilts must be periodic as observed in the experiment. Furthermore, the output field remains at the initial waveguide if a phase difference of integer multiples of π between adjacent waveguides is reached. For the corresponding initial beam tilt the transverse motion of the field in the array is steadily prevented by Bragg reflection at the periodic array structure.

The dependence of the beams transverse motion and its diffractive spreading on the beams input tilt reflects the anomalies in refraction and diffraction in an array. The most striking features are an upper limit of the transverse motion and diffractionless propagation. Evaluating the experimental results we can show these features quantitatively, see Fig. 4. In contrast to isotropic materials, diffractive spreading depends on the angle of incidence. Note that for a tilt of about 1.1°, corresponding to a phase difference of π/2 between adjacent guides, the beam retains its original shape, i.e., diffraction is arrested. Moreover, the angle of diffractionless propagation is that of the maximum transverse shift. One can show that the sign of the diffraction will change if the tilt of the exciting beam exceeds the angle of diffractionless propagation. But this has no effect on the width of the beam and is just as if the beam would travel backwards in space. This is reflected in the experiment by the similar output fields for an initial phase difference of zero and between adjacent guides (see Fig. 2 a, b). Therefore, a tilted array can be used as a simple imaging element.

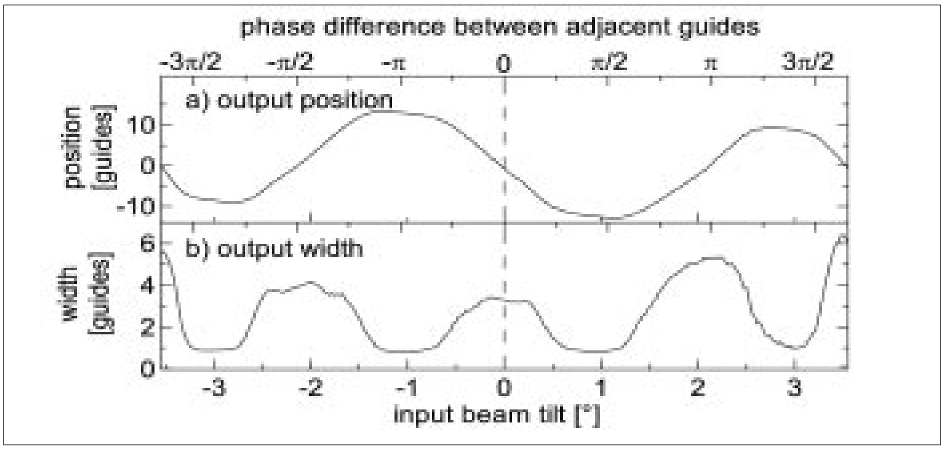

Fig. 4:
Output position (a) and output width (b) determined from the measurements in Fig. 3.

In conclusion, we have studied the propagation of beams in homogenous waveguide arrays. It turned out that refraction and diffraction exhibit strong anomalies as they depend periodically on the initial beam tilt. In contrast to isotropic systems we found that the transverse energy transport cannot exceed a certain maximum velocity and that diffractive spreading depends on the direction of propagation, i.e., by varying the angle of incidence size and sign of diffraction can be controlled and it can even be arrested. For particular initial tilts the array can undo beam spreading. Therefore, a tilted waveguide array can form a simple imaging system.

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## References

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