# Concepts for oblique semi-guided waves: integrated optics with negative effective permittivity

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**Abstract:** Scattering losses are fully suppressed, if guided waves in a high-contrast dielectric slab encounter an elongated obstacle at a sufficiently large oblique angle. We review the underlying arguments and a series of device concepts, including a step transition, high-contrast gratings, and the evanescent excitation of OAM fiber modes.

## Semi-guided waves

Dielectric optical slab waveguides are mostly associated with the standard scalar 2-D TE and TM modes. Taking into account the lateral dimension as well, obvious 3-D solutions for guided waves can be constructed from these, either with an in-plane dependence of infinite plane harmonic waves, or as superpositions of these, in the form of in-plane localized wave bundles, e.g. as beams of Gaussian shape. Things become interesting, if one considers the incidence of these "semi-guided waves" on an elongated discontinuity in the slab, at some not too small angle, and if this happens in a slab of sufficient refractive index contrast [1].

## 2-D integrated photonics with negative effective permittivity

Irrespective of the shape and size of the obstacle, a variant of Snell's law applies, separately for each pairing of incoming and outgoing modes. Power transfer to specific waves is allowed or forbidden, depending on the angle of incidence, and on the effective indices of the fields involved. Critical angles of incidence can be identified, beyond which any power transfer to non-guided waves is suppressed. Then the input power is carried away from the discontinuity exclusively by semi-guided waves.

The problem is governed by vectorial equations on a 2-D cross sectional domain, that are formally identical to the equations for the eigenmodes of 3-D channel waveguides. Here, these need to be solved as an inhomogeneous scattering problem, with the incoming semi-guided wave as a right-hand-side, and subject to transparent boundary conditions. An effective permittivity takes the place of the physical relative permittivity. Depending on the effective index and angle of the incoming wave, that effective permittivity can become locally negative, causing the suppression of propagating nonguided outgoing fields.

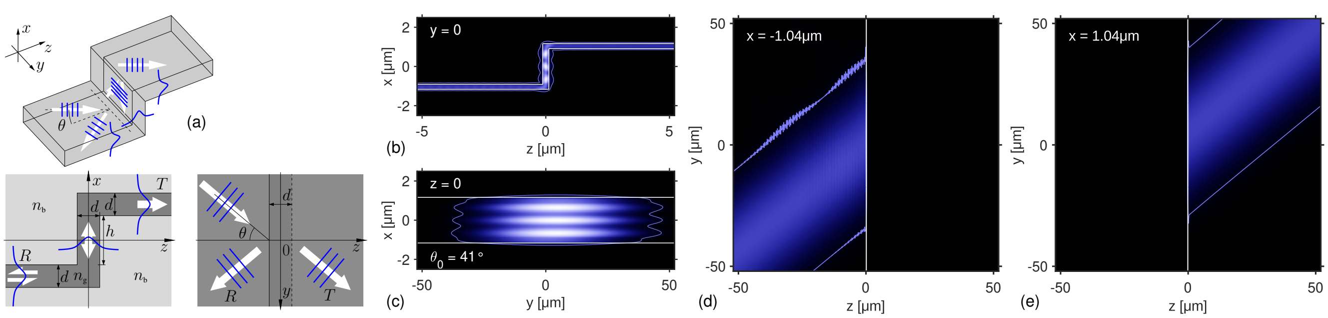


*Figure 1: Oblique incidence of a semi-guided Gaussian beam (TE) at a step structure (a), electromagnetic energy density (b)–(e) for a bundle of $45\,\mu m$ width and angle of incidence $\theta = 41°$. Parameters: $h = 1.83\,\mu m$, $d = 0.25\,\mu m$, $n_g = 3.4$, $n_b = 1.45$, wavelength $\lambda = 1.55\,\mu m$; reflectances and transmittances: $R_{TE} = 0.02$, $R_{TM} < 0.01$, $T_{TE} = 0.96$, $T_{TM} = 0.02$. (Figure adapted from Ref. [2])*

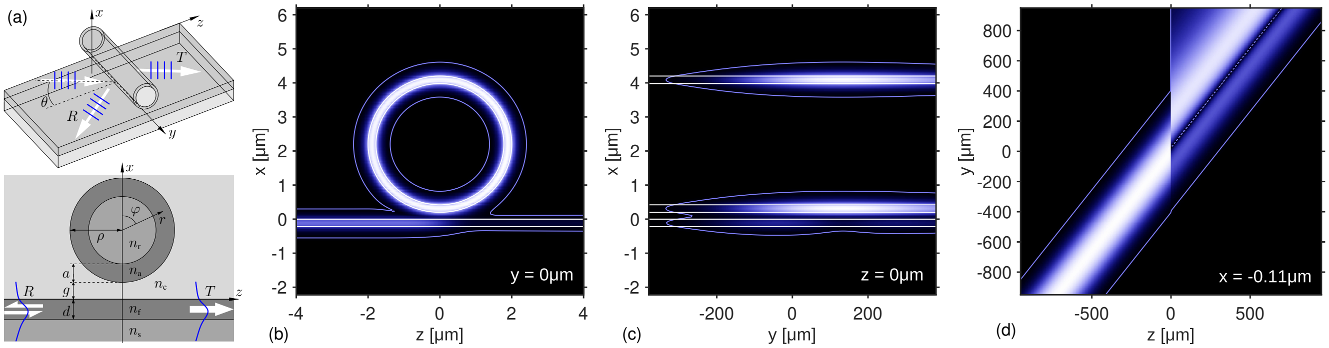


*Figure 2: Evanescent excitation of a coated fiber (a) by a TE-polarized wave bundle of width $224\,\mu m$ at angle of incidence $\theta = 52.85°$ and wavelength $1.55\,\mu m$, absolute electric field (b)–(d). Parameters: $n_s = 1.45$, $n_f = 3.45$, $n_c = 1.0$, $n_r = 1.45$, $n_a = 3.45$; $d = 0.22\,\mu m$, $\rho = 2\,\mu m$, $a = 0.22\,\mu m$, $g = 0.2\,\mu m$. At maximum, the orbital angular momentum (OAM) mode of angular order 13 of the fiber carries about 80% of the input power.* *(Figure adapted from Ref. [3])*

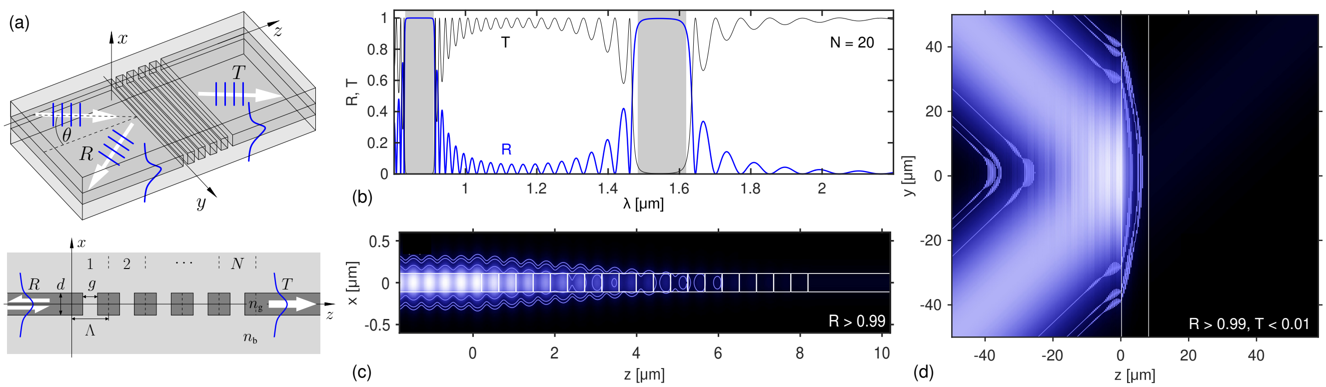


*Figure 3: A high-contrast slab waveguide grating, schematic (a), and cross-section view (b). Results for $N = 20$ periods, for parameters $n_b = 1.45$, $n_g = 3.45$, $d = 0.22\,\mu m$, $\Lambda = 420\,nm$, $g = 10\,nm$, for incoming semi-guided TE waves at angle $\theta = 45°$: Reflectance $R$ and transmittance $T$ versus wavelength $\lambda$ (c), energy density for plane wave excitation (d), and for excitation by a beam of width $35\,\mu m$ (e), at wavelength $1.55\,\mu m$.* *(Figure adapted from Ref. [4])*

## Numerical examples

Figs. 1–3 show some example configurations, for typical parameters from silicon photonics. All fields approximate solutions of the Maxwell equations in the frequency domain, in full 3D. Due to the constancy of the structures along one in-plane axis ($y$, cf. Figs. 1(a)–3(a)), these can be assembled conveniently [2, 3] by analytically superimposing 2-D solutions [5] for some range of angles of incidence. Out-of-plane scattering losses are absent in all cases.

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### References

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