Polarisation Dependent Coupling in Ring Resonator Filters

G.-A. Chakam*, W. Freude*, C. Poulton*, G. von Freymann†, M. Wegener†, and M. Fujii‡

*High-Frequency and Quantum Electronics Laboratory, †Institute of Applied Physics
University of Karlsruhe, Kaiserstr. 12, D-76128 Karlsruhe, Germany
‡Institute for High Frequency Engineering, Technical University München, Arcisstr. 21, D-80333 München, Germany
E-mail: w.freude@etec.uni-karlsruhe.de Web: www-ihq.etec.uni-karlsruhe.de

Abstract — We observed a strong polarisation dependence of the coupling between a straight dielectric strip and a ring waveguide. Based on measurements, we explain this behaviour with numerical and analytical vector-field models for a wedge-type inhomogeneity.

1 Overview

Integrated-optics waveguides are usually high-index contrast structures to allow densely packed substrates and sharp waveguide bends. As a consequence, the devices are polarisation sensitive and need be treated with vector-optics techniques. However, physical intuition usually relies on the dominant transverse electric field component, i. e., on scalar optics. This is the reason that in some cases vector-optics results can be counter-intuitive for strongly guided fields.

The top-view schematic of a side-coupled ring filter is displayed in Fig. 1(b). For the straight high-index single-mode bus waveguides, Fig. 1(a) shows the mode intensity profiles. For the dominantly transverse electric (quasi-)TE field $\vec{E} \approx E_x\vec{e}_x$, Fig. 1(a)(TE), the field extends significantly beyond the side walls of the strip, thus enabling, according to intuition, large coupling gaps between bus and ring. For a dominantly orthogonally polarised (quasi-)TM mode $\vec{E} \approx E_y\vec{e}_y$, Fig. 1(a)(TM), one expects a weaker coupling because of the stronger lateral confinement.

According to 3D full-wave FDTD and FEM simulations, this expectation proves to be false. Standard coupling integrals [1, 2] cannot be applied because they require $\vec{E}$ and the magnetic field $\vec{H}$ to be continuous along x and y. Therefore we checked the numerical findings by measuring a microwave model system, and by analysing the wedge-like coupling zone.

2 Microwave model of ring filter

We designed a microwave model Fig. 1(b),(c), which is up-scaled from optical frequencies around 200 THz (vacuum wavelength $\lambda = 1.5\,\mu$m) by a factor of 20 000, and operates near 10 GHz. The coupling gaps at the left-hand (LHS, $a = 0.4$ mm) and right-hand side (RHS, $b = 0.4$ mm) of the ring are not identical in general [3, 4]. For an off-resonant operating frequency 7.6 GHz, the major transverse electric field amplitudes $E_{x,y}$ are displayed for a time $T \approx 1\,000\,\mu\text{m}/c = 3.3$ ps (vacuum speed of light c) after launching the waveguide mode at $x, z = 0$.

For TE excitation, Fig. 1(b), the coupling between bus and ring is much smaller than for the TM case, Fig. 1(c), and the TE arrangement cannot operate as an efficient filter. Further, a 'hot spot', where the transverse electric field strength becomes very large, is to be seen just after (white arrow in Fig. 1(b)) and also before the coupling zones. Both observations are not easily understood and could have been numerical artefacts. A check of the coupling strength for a reduced FDTD cell size was not feasible because of restrictions in memory (1.5 GB) and run time (48 h).

3 Measurements

We carefully measured the transmission for a notch filter (RHS bus in Fig. 1(b),(c) removed) with coupling gaps varying in the range $a = 0 \ldots 3$ mm. For the TE (TM) case, the maximum attenuation at the resonance frequency 7.845 GHz (7.890 GHz) was 22 dB (30 dB) for $a = 0.05$ mm (0.75 mm). At the anti-resonance frequency 7.72 GHz (7.76 GHz), the attenuation was 0.2 dB (0.5 dB) for the same a. Therefore it may be concluded that the low TE coupling is not caused by radiation losses in the coupling zone, otherwise the anti-resonance loss should be significantly larger than for the TM case.

4 Coupling zone models

An air-wedge in a homogeneous dielectric medium with refractive index n_{strip} models the coupling zone. Because it is small compared to the medium wavelength $\lambda_{\text{strip}} = 10$ mm, a 2D electrostatic analysis will suffice as a first step. For TE polarisation, Fig. 2 veryfies the existence of a large E_x-component ('hot spot' marked by wedge in Fig. 1(b)), which is caused by the singularity at the wedge vertex. The electric field lines are pushed away from the low-index region, so an E_z-component is created to make the field point radially, $\vec{E} \approx E_r\vec{e}_r$. For TM polarisation, the electric field is continuous across the wedge boundaries, so no hot spot is seen, and no significant z-components are created. — A 3D electrodynamic analysis of the wedge analogous to the one performed previously [8] confirmed these findings. — Further, the 3D computation of a high-index version of a Y-junction [9, Fig. 12a] showed the existence of a hot spot just behind the vertex of the waveguide splitting region. — Similar results are obtained when the coupling zone is 2D-modelled by two dielectric cylinders.

In summary, the essentials of the FDTD full-wave analysis leading to Fig. 1(b) are reconfirmed in full.

5 Analytical 2D wedge model

Again we adopt an air-wedge embedded in a homogeneous high-index medium n_{strip} for modelling the coupling region. Following [5, Sect. 4.2], we expand

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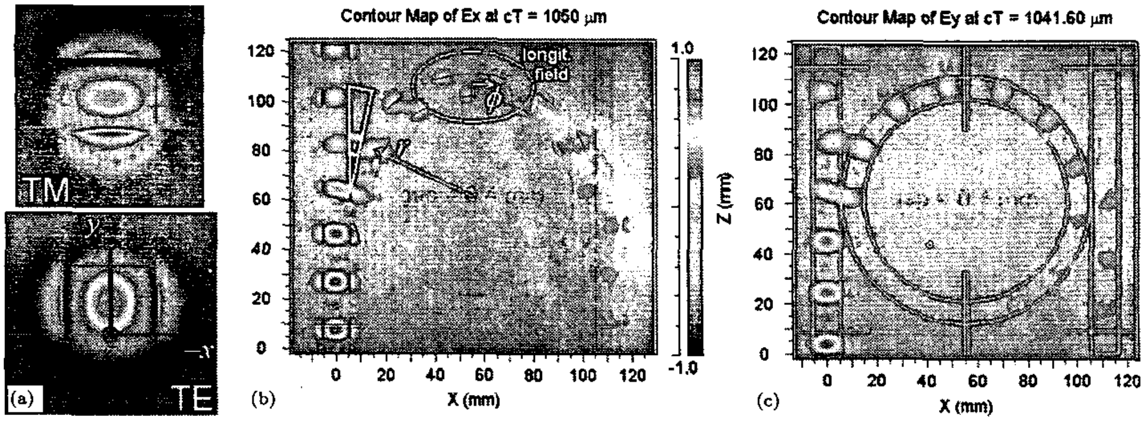

Fig. 1. Mode intensity profiles for straight strip waveguides in TE and TM polarisation, Fig. 1(a). Refractive indices: $n_{\text{strip}} = n_{\text{ring}} = 3.03$, $n_{\text{substr}} = 1.67$ for $y < 0$, $n_{\text{cover}} = 1$. — Full-wave FDTD 3D calculation of major fields $E_{x,y}$ for TE, Fig. 1(b) ($E_x \equiv E_\phi$ in oval region is longitudinal!), and TM excitation, Fig. 1(c). Bus/ring width: 11 mm/9 mm; mean ring diameter: 90.2 mm; height of waveguides: 8.1 mm. Operating frequency is 7.6 GHz. Six narrow rectangles for power flux 'measurement'

the fields in the vicinity of the wedge vertex, and analyse the behaviour of any singularities which may occur there. Provided the refractive index contrast is high, we notice for TE excitation that the electric field within both 'waveguide' regions adjacent to the wedge has a component along the boundaries, and that the electric field is predominantly 'radially' oriented with respect to the ring inside the air-wedge, being larger by a factor n_{strip}^2 compared to the high-index region. For the TM case, the electric field is continuous across the wedge boundaries, see Fig. 1(c), and no singularity is to be seen.

The TE wave in the bus guide does not couple effectively to the ring, because the radially oriented electric field $E_r \approx E_x$ in the coupling zone cannot excite a TE ring mode with a strong azimuthal component $E_\phi \approx E_{x\,\text{oval}}$ (oval region 'longit. field' in Fig. 1(b)). This can be also shown by calculating the energy flux transfered between the wedge boundaries. The TE flux is smaller by a factor n_{strip}^2 than the TM flux.

We remark in passing that a possible decoupling for two straight waveguides was described earlier [6, 7].

6 Conclusion

The coupling between a quasi-TE excited bus and a ring is unexpectedly low. This is due to a mismatch of the electric field, which is dominantly radial in the coupling zone and strongly azimuthal in the ring; the azimuthal component is insignificant in the TM case.

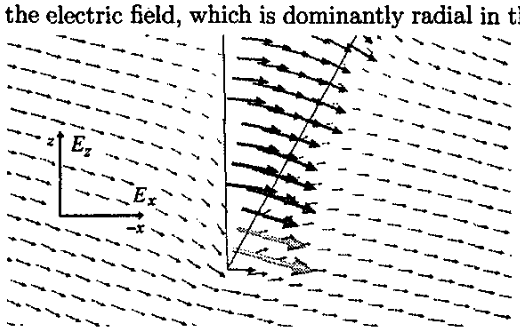

Fig. 2. 2D air wedge in a homogeneous medium with refractive index n_{strip}. Electrostatic field vectors in plane $y = \text{const}$

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