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Grating assisted optical waveguide coupler to excite individual modes of a multi-mode waveguide

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ABSTRACT

Spatial division multiplexing (SDM) in the form of mode division multiplexing (MDM) in multi-mode (MM) waveguides is currently explored to overcome the capacity limitation of single-mode (SM) waveguides in data transmission technology. In this work a new approach towards mode selective optical waveguide couplers to multiplex and demultiplex individual modes of MM waveguides is presented. We discuss a grating assisted mode selective optical waveguide coupler and evaluate numerically its coupling efficiency. The approach relies on a grating structure in a SM waveguide which is used to excite individual modes of an adjacent unmodified MM waveguide via evanescent field coupling. The simulations verify that by using the grating structure and tailoring the grating period, light from the SM waveguide can be coupled selectively into the fundamental mode or any higher-order mode of a MM waveguide with high efficiency and low crosstalk to adjacent mode-channels. The results indicate the potential of the grating assisted waveguide coupler approach for future applications in on-chip photonic networks and the (de)multiplexing of individual modes of MM waveguides.

1. Introduction

Since the maximum data transmission capacity of standard SM fibers is almost reached SDM is currently investigated in order to keep up with the increasing data traffic demand in backbone fiber optic telecommunication applications [1]. One approach of SDM is based on MDM. In this case different modes [2] or mode groups [3] of a MM waveguide are used as individual transmission channels. Main aspects and also challenges of MDM are the scalability of the system to a large number of mode channels with low insertion loss and mode dependent loss, and also modal selectivity. Therefore, adequate mode-selective coupler concepts such as photonic lanterns [4] or tapered couplers [5] have been developed in the past.

MDM can also be beneficial for other photonic applications such as on-chip photonic networks. In this case MDM provides the advantages of increasing the bandwidth density without increasing the number of waveguides and waveguide crossings and, hence, keeping the footprint of on-chip photonic networks small [6]. In terms of on-chip photonic (de)multiplexer, MDM key features are low modal crosstalk and enabling of additional wavelength division multiplexing (WDM) approaches [6]. In the past different concepts of mode division (de)multiplexers based on Y-junction couplers [7], multimode interference (MMI) couplers [8], adiabatic linearly tapered couplers [9], directional couplers [10], ring-resonators in combination with directional couplers [6] or coupled gratings for counter-directional coupling [11] have been reported.

In this paper a new concept for a mode division (de)multiplexer is proposed based on a grating assisted directional waveguide coupler for co-directional coupling. In general, compared to Y-junctions, MMIs and tapered couplers as well as photonic lanterns, directional waveguide couplers enable mode division (de) multiplexing along the optical transmission link with low modal crosstalk as well as low insertion loss and mode dependent loss since, for evanescent mode coupling, the waveguides of the coupler structure only need to be in close proximity to each other. The investigation of mode-selective directional couplers goes back to Whalen et al. [12]. Common mode-selective directional couplers consist on SM and MM waveguides and mode-selective evanescent coupling occurs when the propagation constants of the fundamental mode of the SM waveguide, $\beta_{SM,}$ matches the propagation constants of the fundamental mode or any higher-order mode of the adjacent MM waveguide, $\beta_{MM.}$ In order to fulfill this condition, the propagation constants of the addressed modes of the coupler structure can be optimized during fabrication by e.g. tapering the SM or the MM waveguide (e.g. [6]), respectively. Mode-selective directional couplers have also been realized by using

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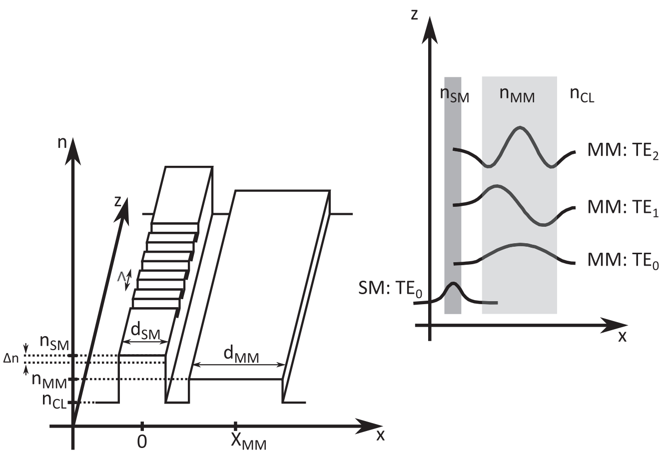

Fig. 1. Refractive index structure of the investigated optical waveguide coupler and the corresponding electric fields of the coupler modes (inset).

surface plasmons [13] or Bloch-modes [14]. However, to date the main limitation of mode-selective directional couplers is the high crosstalk to higher-order modes when only the fundamental mode of non-tapered MM waveguides is excited [14].

To avoid high modal crosstalk, in this paper we investigate the application of a grating for propagation constant matching and hence mode-selective (de)multiplexing. As shown in Fig. 1, the proposed mode-selective coupler structure consists of a SM waveguide comprising a grating structure and an adjacent MM waveguide. Since the propagation constants of the modes of the SM and MM waveguides are mismatched usually no evanescent coupling between the two waveguides occurs. However, when applying a grating structure with an appropriate grating period to the SM waveguide the difference between the propagation constants of an arbitrary mode of the MM waveguide and the fundamental mode of the SM waveguide can be compensated and hence light can be coupled between the modes. Therefore, compared to common mode-selective directional couplers, mode-selective coupling can simply be achieved by adjusting the grating period. Consequently, the proposed grating assisted optical waveguide coupler allows a simple and flexible realization of mode-selective coupling between waveguides.

In the past gratings have been utilized in directional couplers to couple light between mismatched SM waveguides (e.g. [15]) and were applied e.g. as add/drop filters for WDM applications [16,17]. Recently, grating assisted directional couplers have also been investigated for MDM [11]. The mode-selective coupler developed from Chen et al. contained a grating in the SM and in the MM waveguide and was designed for the selective coupling of modes propagating in opposite directions (counter-directional coupling). Since small grating periods are required for the counter-directional coupling this mode-selective coupler exhibits self-Bragg coupling in the SM and MM waveguide and, hence, leads to distortion in the spectral domain. Consequently, to avoid self-Bragg coupling, in this work, a mode-selective directional coupler with a grating structure applied to the SM waveguide only and designed for co-directional coupling is proposed and investigated by using numerical simulations.

2. Concept of grating assisted mode selective waveguide coupler

The basic principle of operation of the proposed grating assisted directional coupler for excitation of individual modes of a MM waveguide is demonstrated by using slab waveguides. The slab waveguide geometry of the coupler structure and the corresponding modes of the SM and MM waveguide are shown in the inset of Fig. 1. The coupling between the fundamental mode of the SM waveguide and an arbitrary mode of the MM waveguide can be described analytically by using the coupled mode theory [18]. When no grating is applied to the coupler structure illustrated in Fig. 1, the electric field propagating through the structure can be described as a linear combination of normal modes:

$$\boldsymbol{E} = \sum_m A_m(z)\bullet\psi(x, y)\bullet e^{i(\omega t-\beta_m z)} \tag{1}$$

where m is the mode index and $\psi_m(x,y)$, A_m and β_m are the eigenmode field, the amplitude and the propagation constant of either the fundamental mode of the SM waveguide or an arbitrary mods of the MM waveguide. However, when a grating structure is incorporated in the SM waveguide in form of a dielectric perturbation light can couple between the modes. Since for resonance coupling conditions only two co-propagating modes of the proposed coupler structure interact, the coupled mode equation can be written as:

$$\frac{\partial}{\partial z}A_1 = -i\kappa A_2 e^{i\Delta\beta z} \tag{2}$$

$$\frac{\partial}{\partial z}A_2 = -i\kappa^* A_1 e^{-i\Delta\beta z} \tag{3}$$

where κ and $\Delta\beta$ specify the coupling coefficient and the phase term between the modes, respectively (* denotes complex conjugate quantities). Both parameters are defined as:

$$\kappa = \frac{\omega}{4}\iint \psi_1^*(x, y)\mu(x, y)\psi_2(x, y)dxdy \tag{4}$$

$$\Delta\beta = \beta_1 - \beta_2 - \frac{2\pi}{\Lambda} \tag{5}$$

In Equation (4) and (5), $\mu(x,y)$ represents a function describing the dependence on the geometry of the grating structure [19] and Λ is the grating period. The solutions for the coupled mode equation and their properties can be found in (e.g. [18]). The exchanged power between the fundamental mode of the SM waveguide (A_1) and any mode of the MM waveguide (A_2) can be determined as:

$$\left|\frac{A_2(L)}{A_1(0)}\right|^2 = \frac{1}{1+\frac{(\Delta\beta/2)^2}{|\kappa|^2}}\sin^2\left(\sqrt{|\kappa|^2+\left(\frac{\Delta\beta}{2}\right)^2}L\right) \tag{6}$$

From Eq. (6) it follows that maximum power is exchanged for resonant coupling ($\Delta\beta=0$) when the coupling coefficient and the coupler length L are equal to $\kappa\cdot L=\pi/2+n\cdot\pi$ (with $n=0, 1, 2,\ldots$).

3. Simulation results

In order to proof the principle of operation we modeled and investigated the above concept of the mode selective optical coupler through the iterative Beam Propagation Method (BPM) (BeamPROP) in RSoft. The parameters of the simulated coupler structure shown in Fig. 1 are summarized in Table 1. The values of the refractive indices of n_{MM} and n_{CL} have been adopted from [20].

The parameters n_{SM}, d_{SM} and d_{MM} have been chosen accordingly so that the waveguide structure considered enables the propagation of a single mode in the SM waveguide and three modes in the MM waveguide. The design is not restricted to this geometry and these parameters. The SM waveguide is modulated by a sinusoidal refractive index change (perturbation) Δn in order to obtain the