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A simple integrated ratiometric wavelength monitor based on a directional coupler

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ABSTRACT

A simple integrated ratiometric wavelength-monitoring device based on a single directional coupler (DC) is proposed and designed. To meet the desired spectral response, a computationally fast method is proposed to optimize the separation distance between two waveguides and the interaction length of the DC based on the local supermodes solution. The wavelength discrimination of the designed structure is demonstrated numerically.

1. Introduction

Wavelength monitors are required in many optical systems such as multi-channel dense wavelength-division multiplexing optical communication systems and fibre-Bragg-grating-based optical sensing systems. A passive ratiometric wavelength monitor offers high-speed wavelength measurement with a simple configuration. It consists of a splitter connected to an edge filter and a reference arm. Alternatively, two edge filters with opposite slopes and overlapping spectral responses can be used to increase the measurement resolution [1,2]. The wavelength of the input signal is determined by the measurement of the ratio of the signal intensities. A ratiometric wavelength measurement scheme can be implemented with bulk devices, an all-fibre based configuration or integrated optical circuits. Compared to bulk optical devices and all-fibre based, integrated wavelength monitors have a compact size, a high scalability and also benefit from a physical robustness. Examples include a multimode interference (MMI) coupler, three single-mode rectangular waveguides, and a Y-branch with an S-bend structure [3–5].

A directional coupler (DC), a basic element of many planar lightwave circuits (PLC), is employed for splitting and combining of light signal through the coupling between two waveguides. The DC is based on a buried silica-on-silicon PLC waveguide as such a structure has the advantages of fibre mode-matching efficiency, low transmission loss, and low polarization dependence [6]. In this paper, we propose the use of a DC optimized for the purpose of wavelength measurement. Compared to an integrated wavelength monitor containing two devices a Y-branch and an edge filter [5], in this approach, a single DC device, implements a ratiometric wavelength monitor. Additionally a computationally fast method to optimize the separation distance and interaction length of the DC is proposed which can be used as an effective design tool compared to a parameter space scanning method.

2. Proposed structure and design method

Fig. 1(a) shows schematic of a simple ratiometric structure based on a directional coupler. It contains a central coupling region and an output region. In the central coupling region, two straight waveguides with an interaction length (L) are separated with a separation distance (s). In the output region, the separation distance is adjusted to avoid coupling between the two output waveguides. The desired spectral response as the ratio of the output power from the two arms of the bar and cross waveguides is presented in Fig. 1(b).

To calculate the outputs of the two arms, a local supermodes solution is used [7]. Based on an analysis of the local supermodes, the relative output powers of the directional coupler are given by

$$P_{bar} = \frac{(1+\cos\ (\phi))}{2} \quad (1.a)$$

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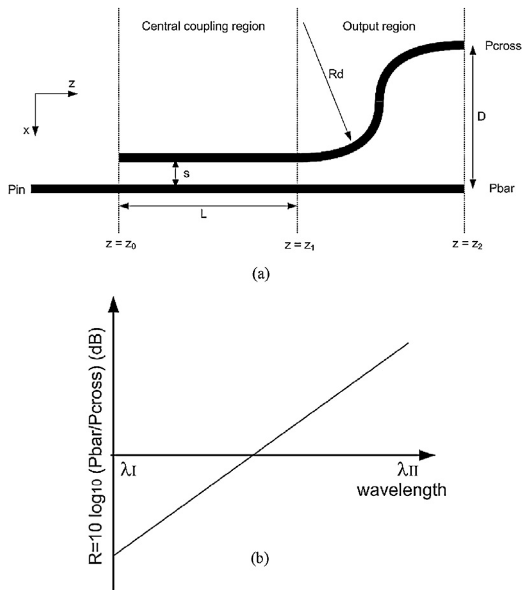

Fig. 1. (a) Schematic structure of a ratiometric wavelength monitoring based on a directional coupler and (b) the desired spectral response.

$$P_{cross} = \frac{(1 - \cos(\phi))}{2} \quad (1.b)$$

where $\phi = \phi_c + \phi_{out}$. ϕ is an accumulated phase difference in the central coupling region and the output region. In the central coupling region from $z = z_0$ to $z = z_1$, as in Fig. 1(a), the phase difference in the central coupling region is given by

$$\phi_c = \frac{\pi L}{L_c} \quad (2)$$

where $L_c = \pi/(\beta_+ - \beta_-)$ is a coupling length. β_+ and β_- are propagation constants of a symmetric and an asymmetric supermodes, respectively. To calculate the propagation constants, a numerical method i.e. a finite difference method [8] can be used.

In the output region up to the output ports, the total phase difference acquired is given by

$$\phi_{out} = \int_{z=z_1}^{z=z_2} \left[\beta_+(z) - \beta_-(z)\right] \, dz \quad (3)$$

At the upper integral limit, $z = z_2$, the coupling between two waveguides is negligible ($\beta_+ = \beta_-$), where the distance D between the two output waveguides is sufficiently large. To calculate β_+ and β_- at positions in the output region in the z direction, the finite difference method [8] could be used, but it is time consuming. A technique [9] which employs a beam propagation method (BPM) can be used more efficiently.

The ratio between the two output powers is determined by the accumulated phase difference as

$$R = 10 \log_{10}\left(\frac{P_{bar}}{P_{cross}}\right) = 10 \log_{10}\left(\frac{1 + \cos(\phi)}{1 - \cos(\phi)}\right) \quad (4)$$

The corresponding ratio with the accumulated phase difference function is shown in Fig. 2. For a desired spectral response for the directional coupler, a simple design method to determine the separation distance (s) and the interaction length (L) is presented below.

The accumulated phase difference can be written in a function of separation distance (s) and a wavelength (λ) as:

$$\phi = \phi_c(s, L, \lambda) + \phi_{out}(s, \lambda) = \frac{\pi L}{L_c(s, \lambda)} + \phi_{out}(s, \lambda) c \quad (5)$$

For a chosen range of wavelengths between λ_I and λ_{II}, the desired ratio is expected to increase from R_I to R_{II}. We can use the graphs in Fig. 2 to choose values of accumulated phase difference ϕ_I and ϕ_{II} for λ_I and λ_{II} which correspond to the ratios R_I and R_{II}, respectively. There are series of ϕ_I and ϕ_{II} values as depicted in Fig. 2. Insertion of these values of ϕ and λ, separately, into (5) produces the two equations:

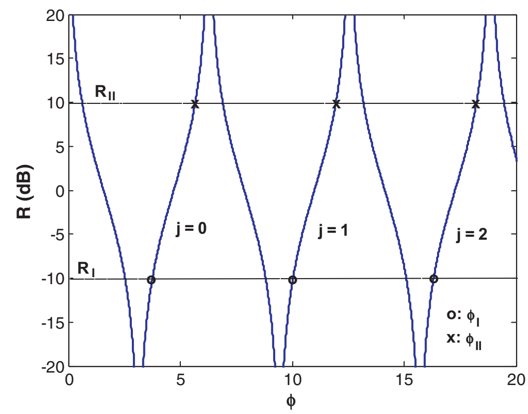

Fig. 2. Dependence of the ratio output power on the ϕ parameter.

$$\phi_I = \frac{\pi L}{L_{c,\lambda_I}(s)} + \phi_{out,\lambda_I}(s) \quad (6.a)$$

$$\phi_{II} = \frac{\pi L}{L_{c,\lambda_{II}}(s)} + \phi_{out,\lambda_{II}}(s) \quad (6.b)$$

After elimination of L and combination into a single equation in terms of the variable s, an objective function can be defined as:

$$f(s) = \frac{\phi_I - \phi_{out,\lambda_I}(s)}{\phi_{II} - \phi_{out,\lambda_{II}}(s)} - \frac{L_{c,\lambda_{II}}(s)}{L_{c,\lambda_I}(s)} \quad (7)$$

By using the chosen values of ϕ_I, ϕ_{II}, and utilizing (7), the optimum value of s can be obtained which corresponds to $f(s) = 0$. Thus, the optimum value of L can be extracted from either of (6.a) or (6.b). Multiple values exist for the parameter pair ϕ_I and ϕ_{II}, as seen in Fig. 2, therefore multiple values of S and L which are possible but in practice the value of ϕ_I and ϕ_{II} which yields a viable device size is chosen. The design steps can be summarized as follows:

1. For a range of separation distances (S), the values of L_C and ϕ_{out} for λ_I and λ_{II} are calculated.
2. The desired spectral response R_I to R_{II} which corresponds to ϕ_I and ϕ_{II}, Eq. (7) is used to determine the separation distance, S.
3. Either Eqs. (6.a) or (6.b) is used with the obtained s to calculate the interaction length (L).

The proposed method involves much less computation by comparison to a parameter space scanning method (for S and L of the DC), to meet the desired spectral response. If the BPM is used, there is a need to calculate P_{bar} and P_{cross} for N_1 – wavelengths, N_2 – separation distances and N_3 – interaction lengths. Thus there are $N_1 \times N_2 \times N_3$ computations required to obtain the desired spectral response. The method proposed here only needs to calculate L_C and ϕ_{out} for two wavelengths and N_2 – separation distances.

3. Numerical example and discrimination demonstration

To demonstrate the design method and the ratiometric scheme, we present a numerical example. The refractive indices of the core and cladding for a buried silica-on-silicon waveguide are denoted as n_{co} and n_{cl}, respectively, the height and width of the core is h_y and h_x, respectively. We choose typical waveguide parameters as $h_x = h_y = 5.5$ µm, refractive index difference $\Delta n = 0.75\%$ ($n_{co} = 1.4553$