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Planar prism spectrometer based on adiabatically connected waveguiding slabs

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ABSTRACT

The device principle of a prism-based on-chip spectrometer for TE polarization is introduced. The spectrometer exploits the modal dispersion in planar waveguides in a layout with slab regions having two different thicknesses of the guiding layer. The set-up uses parabolic mirrors, for the collimation of light of the input waveguide and focusing of the light to the receiver waveguides, which relies on total internal reflection at the interface between two such regions. These regions are connected adiabatically to prevent unwanted mode conversion and loss at the edges of the prism. The structure can be fabricated with two wet etching steps. The paper presents basic theory and a general approach for device optimization. The latter is illustrated with a numerical example assuming SiON technology.

1. Introduction

In the early years (70's) of Integrated Optics (IO), the theory and experimental characterization of slab waveguide based components, such as thin film lenses, prisms, reflectors and polarization splitters were extensively investigated [1]. The design of these components is straightforward since the propagation of light waves in these slabs can be described by geometrical optics in 2D and diffraction theory [2]. Furthermore, slab waveguide fabrication is not a complicated process. In spite of these advantages, only a small number of device principles, which combines one or more of these components, have been implemented, like prism based mode separators [3], grating based de-multiplexers [4] and thermo-optic switches [5].

Wavelength (de)multiplexing planar devices, or micro-spectrometers, have a large potential for applications in telecommunication and sensing [6–10]. In planar implementations the device principle is often based on IO variants of bulky grating spectrometers like an arrayed waveguide grating (AWG) [6], employing diffractionless propagation in waveguides and compact Echelle gratings [9,10]. In addition, cascaded Mach–Zehnder interferometers and ring resonators are being used [11,12] as micro-spectrometers. In particular, the AWG is quite often applied owing to its robustness and high resolution compared to the device area. The latter is related to the working principle of the device based on the use of higher diffraction orders, which also leads, as a possible disadvantage, to spectral overlap (limited free spectral range) and loss via spreading of the intensity over a number of orders. The advantages of employing a prism-based spectrometer are the absence of extra diffraction orders (no power splitting) and an unlimited free spectral range.

In this paper, we describe the performance and design aspects of a miniature prism spectrometer, which can be fabricated in a relatively simple way with adiabatically connected slab waveguides (having two different thicknesses), using in the design principles of geometrical optics and diffraction theory. In such a spectrometer dispersion is introduced by the differing wavelength dependence of the effective indices of the modes in thin and thick films. The device relies on ridge waveguides for light transport and on parabolic mirrors for collimation and focusing. A design strategy will be presented and illustrated via a numerical example with TE polarized light in a range of 100 nm around the central wavelength of $\lambda_c = 850$ nm with a channel spacing of 5 nm by using SiON waveguide technology.

The rest of this paper is organized as follows. First, we will introduce the principle and basic theory related to the prism spectrometer in Section 2. The part of the imaging theory discussed in this section is well usable for other Integrated Optics based spectrometer types, such as AWGs. It is followed by an

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explanation of the design of this device in Section 3, where also a numerical example is given. The paper ends with conclusions in Section 4. A preliminary account of this design strategy has been given in [13].

2. Prism spectrometer: principle and basic theory

A schematic picture of the considered prism spectrometer device is shown in Fig. 1. It is composed of an input waveguide, a collimating mirror, a prism slab, a focusing mirror and receiver waveguides, corresponding to different wavelengths. The picture in the middle of Fig. 1 with output of 3 adjacent waveguides shows the important spectrometer parameters that will be used in this paper, such as 3 dB bandwidth ($\Delta\lambda$), channel spacing ($\Delta\lambda_{cs}$), adjacent channel cross-talk (ACCT), global cross-talk (CT) and Loss.

The proposed device is planned to be implemented in SiON waveguide technology by using a stoichiometric Si_3N_4 (nitride) layer sandwiched between buffer and cladding SiO_2 (oxide). Patterning of nitride will be done by using a BHF wet etching process, which has a very low etch rate being 0.9 nm/min [14] and so very controllable etching performance, in two different process steps; (i) definition of input/output waveguides and (ii) definition of prism and mirror trenches. A sacrificial oxide layer is deposited on top of the nitride layer in the latter in order to achieve the adiabatic transition on the edges of patterned structures. The main advantage of using an adiabatic transition of the layer thickness, and thus the effective refractive index, between the slab waveguides is the elimination of partial reflection of the incident light at the edges of the prism [1]. With such a tapering the angle of incidence to the prism can be chosen relatively high (just below the critical angle θ_{crit}), which is beneficial for a larger angular dispersion (enabling a smaller device area for a given resolution) as discussed below (Section 2.1), without increasing insertion loss and the amount of stray light in the spectrometer. These adiabatic transitions also affect the modal phase shift upon total internal reflection (TIR) by the mirrors and so the imaging onto the receiver waveguides. This will be elaborated in Section 2.4. In the following subsections we will present the basic theory for the set-up, relevant for device design and operation.

2.1. Prism

A sketch of the prism is shown in Fig. 2, where also the ray trajectory is indicated and used symbols are introduced.

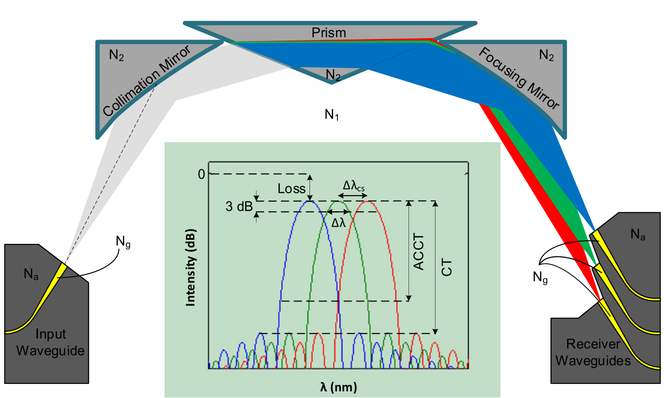

Fig. 1. Schematic of the considered prism spectrometer. The white and dark gray areas correspond to thick and thin slabs, respectively. Ridge waveguides are indicated by yellow lines. The inset illustrates schematically the relation of the output intensities to the parameters that characterize the device performance. Regions with different thicknesses of the guiding layer are connected adiabatically via vertical tapering. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

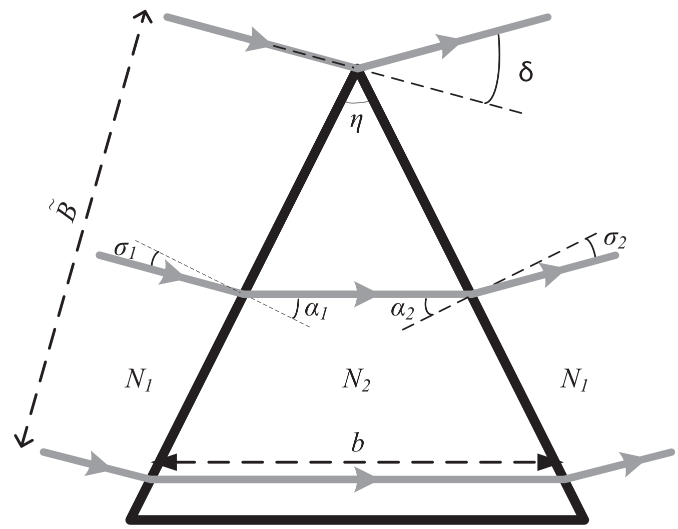

Fig. 2. Schematic (top view) of a generic prism structure.

The angular dispersion is defined by

$$\sigma_2' = \partial\sigma_2/\partial\lambda, \tag{1}$$

where λ is the (vacuum) wavelength. The angular dispersion can be rewritten as follows: Diffraction at the prism interfaces is governed by Snell's law. For the first interface, this can be written as

$$\sin\sigma_1 = D\sin\alpha_1, \tag{2}$$

where we defined $D = N_2/N_1$, with N_1 and N_2 the effective indices of the thick and thin slabs, respectively. Note that the following inequality holds for $N_2 < N_1$. Knowing that σ_1 does not depend on λ, the derivative of Eq. (2) gives

$$\alpha_1' = -\frac{D'}{D}\tan\alpha_1, \tag{3}$$

with $D' = \partial D/\partial\lambda$. The relation between α_1 and α_2 can be found from the geometry leading to

$$\alpha_1 + \alpha_2 = \eta. \tag{4}$$

By combining Eqs. (3) and (4) we arrive at

$$\alpha_2' = \frac{D'}{D}\tan\alpha_1. \tag{5}$$

If Snell's law is applied to the second interface it follows

$$\sin\sigma_2 = D\sin\alpha_2, \tag{6}$$

from which the following can be obtained by taking the derivative,

$$\sigma_2' = D'\frac{\sin\alpha_2}{\cos\sigma_2} + D\alpha_2'\frac{\cos\alpha_2}{\cos\sigma_2}. \tag{7}$$

The above equality can be rewritten by inserting Eqs. (5) into (7) as follows:

$$\sigma_2' = D'\left(\frac{\sin\alpha_2}{\cos\sigma_2} + \frac{\sin\alpha_1\cos\alpha_2}{\cos\alpha_1\sin\sigma_2}\right). \tag{8}$$

for later use we consider the angular dispersion, assuming minimum deviation ($\alpha_1 = \alpha_2$, $\sigma_1 = \sigma_2 = \sigma$), which can be re-written from Eq. (8) into:

$$\sigma_2' = \frac{D'}{D}(\tan\sigma + 1). \tag{9}$$

The deviation angle δ can be expressed as