The numerical analysis of integrated photonics structures for optical beam deflection application

Przemysław Struk

Department of Optoelectronics, Faculty of Electrical Engineering, Silesian University of Technology, 2 Krzywoustego Str. 44-100 Gliwice, Poland

Received May 29, 2024; accepted June 29, 2024; published June 30, 2024

Abstract—The paper presents a concept and numerical analysis of a fast scanner based on integrated photonics structures, including a planar waveguide with a grating coupler combined with a swept source laser as a light source.

In the modern optoelectronics field, the core issue is the development of integrated photonics structures for guiding, modifying, and changing light beam propagation direction [1-7]. The manuscript presents the concept of the integrated photonics structure based on a planar waveguide and grating coupler combined with a source-swept laser for deflection of the light beam. The swept source lasers are usually applied in the optical coherence tomography technique to visualize the examined structure [8-10]. However, the swept source, thanks to its properties of wavelength changing of light in a fast way, can also be applied in integrated photonics structures for deflection of the light beam α_{out} according to wavelength changing and with speed equal to the frequency of swept rate f_a. This phenomenon can be used for fast deflection of light in fast scanner applications. The concept of photonics structure for deflection of the light beam is presented in Fig. 1. The swept source is applied as a light source for excitation of waveguide modes, which propagate in the waveguide layer based on ZnO wide band gap semiconductor deposited on BK7 glass. The waveguide mode propagates in the planar waveguide and arrives at the grating coupler, which is uncoupled to cladding.

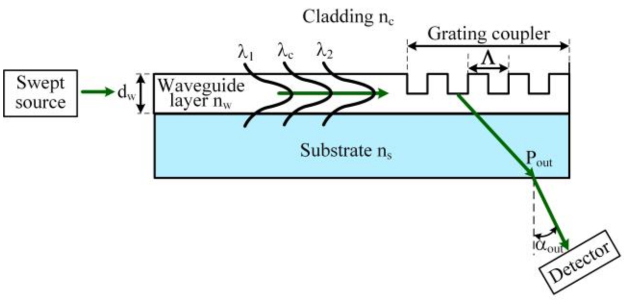

Fig. 1. Scheme of analysed photonics structure.

The principle of operations of the structure is based on changing of output angle α_{out} according to changes in wavelength λ generated by the swept source. The mathematical equation describing the uncoupling of light from the waveguide by grating coupler to cladding is presented below [11-13]:

$$\beta_c sin\,(\alpha_{out}) = \beta_w + \frac{m_o 2\pi}{\Lambda}, \qquad (1)$$

where: β_c, β_w - propagation constant in environment and waveguide respectively, Λ - space period of the grating, m_o - diffraction order, α_{out} - the angle of uncoupling of light.

The critical issue is the analysis of the light beam output angle α uncoupled from structure to cladding as a function of wavelength changes generated by the swept source. The output angle α_{out} of the light beam in the grating coupler is defined by the equation [11-14]:

$$\alpha_{out} = arcsin\left[\frac{1}{n_c}\left(N_{eff} - \frac{m_o\lambda}{\Lambda}\right)\right], \qquad (2)$$

where: λ - wavelength, N_{eff} - effective refractive index, n_c – refractive index of cladding.

The analyses were performed assuming the properties of swept source laser (ESS840 Exalos) parameters presented in Table 1 [15].

Table 1. Properties of swept source laser.

Central wavelength λ_c	S range $\Delta\lambda$	Swept frequency f_a
840nm	60nm	100 kHz

The geometrical properties of analyzed photonics structures, including planar waveguide and grating coupler, are presented in Table 2.

Table 2. Geometrical properties of structure.

Period of grating Λ	Depth of grating grooves	Waveguide thickness
800 nm	50 nm	300 nm

The refractive index of each layer in the analyzed structure for wavelength at the edge of the swept range: the shortest wavelength λ_1 -, central wavelength λ_c, and the longest wavelength λ_2 of each is presented in Table 3 [16].

Table 3. The refractive index of the waveguide layer and substrate.

Wavelength	Waveguide ZnO n_w	Substrate BK7 glass n_s
λ_1 = 810nm	1.9580	1.5106
λ_c = 840nm	1.9549	1.5100
λ_2 = 870nm	1.9505	1.5092

The numerical analysis was focused on two steps. The first numerical analysis focused on determining modal characteristics of the structure - effective refractive index N_{eff} as a function of waveguide thickness d_w. The modal characteristic was calculated for three wavelengths, including the shortest wavelength λ_1, central wavelength λ_c, and the longest wavelength λ_2 in the swept laser range, and for waveguide layer thickness in the range from $d_w = 0$ µm to $d_w = 0.4$ µm. Numerical analyses were performed using OptiFDTD software (Optiwave Systems Inc., Canada).

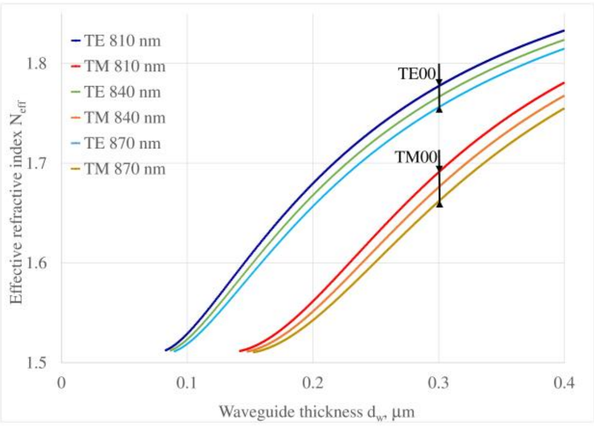

Fig. 2. Modal characteristic of waveguide structure.

The modal characteristic of waveguide structure shows that the effective refractive N_{eff} index for each waveguide mode decreases according to the wavelength of light λ increase. In addition, the minimal thickness of the waveguide layer d_w for which waveguide mode can propagate into structure increases according to the wavelength of light increases. The value of the effective refractive index N_{eff} for waveguide thickness d_w = 300 nm was considered during the analysis of the light beam deflection angle α_{out}. The deflection of the light beam for Transverse Electric (TE00) and Transverse Magnetic (TM00) waveguide mode is presented in Fig. 3 and Fig. 4, respectively. The angle at which light is uncoupled from the structure (relative to the normal) for the TE00 modes and the diffraction order $m = 1$ is in the range of $\alpha_{out} = 49.9$ ° to $\alpha_{out} = 42.9$ °, for the second diffraction order $m = 2$ the $\alpha_{out} = -14.3$ ° to $\alpha_{out} = -24.8$ °. In the case of moduTM00, the range of changes in the angle of light uncoupled form structure is for the first diffraction order m=1 $\alpha_{out} = 42.7$ ° to $\alpha_{out} = 35.2$ °, and for the second diffraction order $\alpha_{out} = -19.5$ ° to $\alpha_{out} = -30.7$ °.

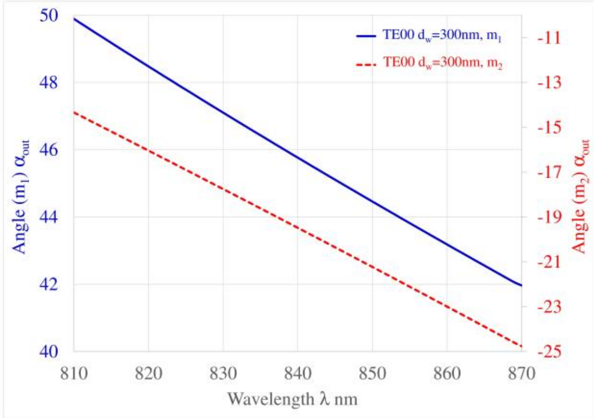

Fig. 3. Changes of output angle α_{out} during laser swept for TE polarization mode.

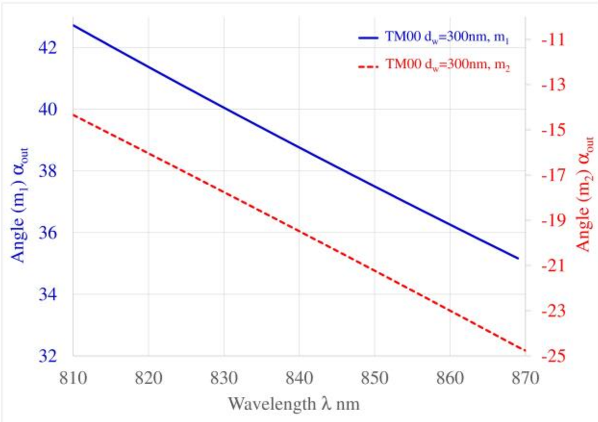

Fig. 4. Changes of output angle α_{out} during laser swept for TM polarization mode.

The presented concept of the structure allows deflection of the light beam $\Delta\alpha_{out}$ at the level of from 0° to 7.93° or 11.17° degrees with f = 100 kHz rate depending on grating diffraction and polarization of waveguide mode Table 4.

Table 4. Analysis of angle deflection.

Waveguide mode			
TE	TE	TM	TM
Diffraction order of grating m			
1	2	1	2
Change of output angle $\lvert\Delta\alpha_{out}\rvert$ °			
7.93	10.42	7.56	11.17

The paper presents the concept of applying integrated photonic structures in the form of planar waveguides with a grating coupler for the deflection of light beams according to the sweep of the laser source. This solution has a high potential application in fast scanner devices where the beam must be deflected according to the swept source rate. In addition, the presented structure could be applied in sensor applications, where changes in effective refractive index N_{eff} cause changes in the out-angle range of the light beam. The key advantage of the presented concept is a large scale of structure integration — and high light deflection rating according to the laser's swept rate.

References

[1] L. Thylén *et al*., Photon. Res. **2**(2), 75 (2014).
[2] P. Cheben *et al.*, Nature **560**(7720), 565 (2018).
[3] D. Zhu *et al*., Adv. Opt. Photonics **13**, 2 (2021).
[4] S Ura *et al*., Opt. Express **16**, 16 (2008).
[5] A. Ymeti *et al*. Appl. Opt. **42**, 28 (2003).
[6] E. Auguściuk et al., Phot. Lett. Poland **2**(2), 70 (2010).
[7] K. Ezgi *et al.*, Phot. Lett. Poland **15**(3), 42 (2023).
[8] A.Y. Alibhai, Curr. Ophthalmol. Rep. **6**, 7 (2018).
[9] Y. Chen, *Atlas of Swept Source OCT and OCT angiography* (Springer 2023).
[10] P. Struk *et al*., Opt. Lett. **43**, 19 (2018).
[11] P. Struk, Materials **12**, 175 (2019).
[12] W. Lukosz, Sens. Actuators B Chem **29**(1-3), 261 (1995).
[13] P.V. Lambeck, Meas. Sci. Technol. **17**(8), R93 (2006).
[14] P. Struk, Phot. Lett. Poland **12**, 2 (2020).
[15] Exalos ESS-840 datasheet.
[16] https://refractiveindex.info

