Optical Power Splitter Based on Single Mode Directional Coupler Waveguide Using SnO₂ Nanomaterial

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Abstract. Optical power splitter based on waveguide had been simulated numerically using Finite Difference Beam Propagation Method (FDBPM). Proposed waveguide was designed in the form of simple directional coupler waveguide. The waveguide was contained SnO₂ nanomaterial as film or the guide part and the other supporting material as cladding with lower refractive index such as flint glasses. The waveguide used 2 µm of width to establish single-mode waveguide. The structure of waveguide is divided into three parts such as input, coupling and output part. While the waveguide was modified with angle in input and output parts to avoid coupling between waveguides. Furthermore, the proposed waveguide was analysed by varying the angle and coupling length. The analysed result shows that the waveguide has best performance in angle of 0.5 degrees and coupling length of 300 µm when the propagation loss was around 0.53%. Using the parameter, the output distribution percentage of waveguide approached 55%:44.5%. This performance indicated that the proposed waveguide can be used as optical power splitter. The application is very useful for optical telecommunication networking development.

1. Introduction
During the current COVID-19 pandemic, long-distance telecommunication has become very important. The telecommunication device is necessary to continue some activities without having to meet each other. Optical device is one of the best alternatives to support development of the telecommunications. Optical telecommunication can produce ultra-fast and more effective communications, especially in the data transfer.

The process data transfers in the current telecommunication has already used optical fiber or optical waveguides. However, the transfer process is still obtained losses due to various factors. One of them occurs in branching due to the wider network. Many researchers are still looking for solutions to reduce these losses. The most popular methods are modifying the branching design of the Y waveguide [1], changing the coupling parameters of the directional coupler waveguide [2,3], and making use of the waveguide containing optical nonlinear materials [4]. Previous research has shown that nonlinear waveguides can switch signals at speeds up to terabits per second [5]. This high speed is one of the reasons why nonlinear waveguides are still the concern of many researchers until now.

In this study, the data transfer process was represented by power splitter will be investigated on a directional coupler-based waveguide. The waveguide contains SnO₂ nanomaterial as an optical nonlinear material. SnO₂ material was chosen because of many advantages such as high refractive index (2.006-2.486), high transparency (43.8-75% in visible light region), high conductivity (~10⁻³ cm)¹, and
wide bandgap (≥ 3.6 eV) and high nonlinearity coefficient [6,7]. SnO$_2$ has been developed and applied in research on waveguides such as optical logic gates [8,9] and optical divider [10]. The waveguide in this study was also developed by modifying its parameters. The waveguide was generated to be single-mode waveguide to obtain lower losses. In the future, it is hoped that the design and simulation of waveguides in this research can help the development of optical telecommunications.

![Figure 1. The proposed waveguide design](image)

| Waveguide Parameter                  | Unit symbol | Value          |
|--------------------------------------|-------------|----------------|
| Input/output length                  | $L$         | 200 µm         |
| Coupling length                      | $L_{c}$     | 500 µm         |
| Film/core width                      | $d$         | 2 µm           |
| Gap                                  | $g$         | 1.4 µm         |
| Angle                                | $\theta$    | 1°             |
| Refractive index of film/core        | $n_{co}$    | 2.006          |
| Refractive index of cladding         | $n_{cl}$    | 2.000          |
| Wavelength of input signal           | $\lambda$   | 632.8 nm       |
| Propagation constant                 | $\beta/k_0$ | 2.0038445086913765 |
| Nonlinearity coefficient of Kerr     | $\alpha$    | $1.7 \times 10^{-11}$ m$^2$/V$^2$ |

2. Waveguide Design and Method

Figure 1 illustrates the proposed waveguide that designed in parallel straight waveguide as based of directional coupler. The structure of waveguide consists of three parts that are input part, central part, and output part. The input and output part of structure were arranged with a certain angle ($\theta$) to avoid coupling effect. While the coupling phenomena was expected to occur in central part to generate power splitter function. Therefore, the part was built with two straight waveguide which separated a slight gap ($g$). In this study, the gap was chosen as 1.4 µm. The waveguide consists of SnO$_2$ nanomaterial as film or core and the other material with lower material such as flint glass where the refractive index of core ($n_{co}$) and cladding ($n_{cl}$) are 2.006 and 2.000 respectively. According to the previous research, SnO$_2$ has
high nonlinearity coefficient which is \( \alpha = 1.7 \times 10^{-11} \text{m}^2/\text{V}^2 \). While the wavelength of input signal is chosen by \( \lambda = 632.8 \mu\text{m} \). Nonlinear material was placed in the central part where coupling was happened to increase obtained output power [11].

As single mode directional coupler, the proposed waveguide width (\( d \)) was arranged to ensure that the propagated signal was in basic mode TE0. The mode of propagated optical signal was represented by effective refractive index or better known as propagation constants (\( N = \beta/k_0 \)) which can calculate using dispersion relation equation that showed in equation 1.

\[
f(x) = k_0 h \sqrt{n_f^2 - N^2} - \tan^{-1} \left( \frac{n_f^2 - n_e^2}{n_f^2 - N^2} - \tan^{-1} \left( \frac{n_f^2 - n_e^2}{n_f^2 - N^2} \right) \right)
\]

Numerical calculation of equation results dispersion relation graph was described in Figure 2. It represented how many modes that propagated according to the film/core width. As the results, basic mode was occurred while the core width in range of 0.9 – 2 \( \mu \text{m} \). The widest size was chosen to make the fabrication process easier. While \( d = 2 \mu\text{m} \), the propagation constant was obtained on, \( \beta/k_0 = 2.0038445086913765 \). The overall parameter of waveguide summarized in Table 1.

![Figure 2. Dispersion relation of propagated optical signal mode in waveguide](image)

Furthermore, signal propagation in the proposed waveguide was simulated using Finite Difference Beam Propagation Method (FDBPM) which as one of numerical calculation tools to solving differential equation for wave function during propagate in nonlinear waveguide that written by equation 2.

\[
\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} - 2jk_0N\frac{\partial u}{\partial z} + k_0^2 \left( n^2 - N^2 \right) u + k_0^2 \alpha(x, z) |u|^2 u = 0
\]

In the study, the problem of waveguide simulation was reduced to have one-dimensional index profile in the cross section by defining effective indices to various parts of practical two-dimensional structures. The propagation of signal was built in cartesian area with \( |x| < x_{\text{max}} (= 25 \mu\text{m}) \) by calculating of the homogeneous grid with interval of the transverse coordinate as \( Ax = 0.05 \mu\text{m} \) and \( Az = 1 \mu\text{m} \) in the propagation direction. For analysis process, input signal was given just on one the input port. The output port in the same line with input signal was labelled with P1 since the other output port is P2. Both of output ports was comparing to achieve better power splitter application.
3. Result and Discussion
The study analysis was carried out by parameter optimization to obtain best performance of waveguide, especially as power splitter. Firstly, parameter of angle in input and output part should be optimized. Angle was varied in three value which are 0.5°, 1°, and 1.5°. Table 2 shows output power distribution from the simulation results by varying the angle. According to the results, the smallest value of angle produces the best performance which is obtained smallest propagation loss. It is because bent in waveguide with angle can cause signal scattering as one of reason of propagation loss. Smaller angle parameter can avoid the scattering effect and obtain smaller loss [1]. Therefore, 5° of angle was chosen as fixed parameter of waveguide for further analysis.

Table 2. Output power distribution by varying in angle parameter

| Angle (deg.) | Output Power in P1 (%) | Output Power in P2 (%) | Propagation Loss (%) |
|--------------|------------------------|------------------------|---------------------|
| 0.5          | 30.1                   | 68.7                   | 1.16                |
| 1.0          | 28.2                   | 66.8                   | 5.05                |
| 1.5          | 21.7                   | 67.7                   | 10.6                |

Coupling length parameter is one of important parameter that should be considered while perform directional coupler. In the next analysis, wave propagation in the waveguide was analysed by varying coupling length parameter in the central part. The coupling length was varied in 300 µm, 400 µm, and 500 µm. Table 3 shows output power distribution from simulation results by varying coupling length. The results indicated that power distribution had been divided almost stable while coupling length of 300 µm and 400 µm was used. It clarifies that the wave function of signal has propagated on a half beat cycle in spatial length between 300 µm and 400 µm. While in coupling length of 500 µm, power distribution of output signal tends to P2. It due to the signal begin to transmit into another waveguide in that length. The best coupling length value of power splitter waveguide is 300 µm. The value results almost balance distribution of power splitter and the lowest propagation loss. The simulation results of signal propagation in the proposed waveguide can be observed in Figure 2. The results confirm that longer the coupling length parameter between 300 µm to 500 µm, more periodic the deflection of the signal in coupling part. It can be reason why the propagation loss became higher.

Table 3. Output power distribution by varying in coupling length parameter

| Coupling length (µm) | Output Power in P1 (%) | Output Power in P2 (%) | Propagation Loss (%) |
|-----------------------|------------------------|------------------------|---------------------|
| 300                   | 55.0                   | 44.5                   | 0.53                |
| 400                   | 43.4                   | 55.8                   | 0.84                |
| 500                   | 30.1                   | 68.7                   | 1.63                |

Table 4. Comparison of previous studies with the proposed waveguide

| No | Reference | Waveguide Type | Material | Coupling ratio | Losses |
|----|-----------|----------------|----------|----------------|--------|
| 1  | [12]      | Multi-mode DC  | Optical Fiber | 50.2:49.2      | 14.6% |
| 2  | [10]      | Multi-mode DC  | SnO₂      | 44.4:44.14     | 0.78% |
| 3  | Antenna proposed | Single-mode DC | SnO₂      | 55:44.5        | 0.53% |
Figure 3. Propagation of signal on the proposed waveguide with coupling length of (a) 300 µm; (b) 400 µm; and (c) 500 µm
According to Table 4, the proposed waveguide has advantage by comparison with previous studies. The waveguide in this study obtains the smallest losses, that is 0.53%. It is due to the waveguide is a single-mode waveguide and contain nonlinearity from SnO$_2$ material which can improve the output power percentage. The power distribution also quite balance and can be considered as power splitter for telecommunication networking applications.

4. Conclusion
A power splitter based on single-mode directional coupler waveguide using SnO$_2$ nanomaterial had been simulated using FDBPM. On the coupling part, the core of waveguide contains nonlinearity of SnO$_2$ to increase output power. According to the results of simulation, the angle of 5$^\circ$ was chosen as an angle to arrange input and output parts because it obtained the smallest propagation loss. While the best coupling length parameter is 300 µm because it achieved more balanced output power distribution and has the smallest propagation losses. Comparing with previous studies, the proposed waveguide has the best performance in terms of waveguide losses which is 0.53%. The performance can be considered the waveguide to be applied as power splitter for optical telecommunication networking development.

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