Flexible and Low-Cost Fabrication of Optical Waveguides Based on SnO₂ for Passive Optical Devices

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Abstract. A process for fabricating fully integrated optical devices based on tin oxide material using a laser cutting method had been conducted. This study was able to create optical waveguide channels in a flexible and fast way using the method. The study also demonstrated that the laser cutting process was capable of fabricating a Y-double branch optical waveguide based on the core material SnO₂ designed using the PMMA substrate. The fabrication structure was analyzed for the input and output of the optical waveguide design. In the future, this process will be enormous to improve the design and rapid manufacture of optical waveguide structures for passive optical device applications.

1. Introduction

Optical waveguides are one of the passive devices integrated with photonics systems and telecommunication system networks initially starting from laboratory research. This device can transmit and modify optical signals from one point to another [1]. Therefore, various intensive studies are currently being carried out to develop effective and efficient optical waveguides both in terms of performance and fabrication costs. In general, optical waveguide fabrication is made from photolithography [2], reactive ion etching [3], hot embossing process [4], and direct ultraviolet (UV) writing [5]. These various fabrication methods require complex supporting equipment which is very expensive and a strictly controlled environment. An alternative method for producing easy and inexpensive optical waveguides is through laser engraving [6]. Previously, laser engraving has been used in various applications such as D-type optical fibre fabrication [7], LiNbO₃ crystal fibre [8], optical fibre made of polymer [9], and PCB-based channel fabrication [10].

One of the most basic geometries of optical waveguides is the Y-branch, where the geometry can divide optical power symmetrically. The Y-branch waveguide (1x2) has an optimal function as an optical power splitter, but it can also be used as a directional coupler [11], optical combiner, and optical switch [12]. The structure of the optical waveguide generally consists of substrate, core, and cladding. Various materials have been used as the core material in optical waveguides such as silica, optical fibre plastics, epoxy resins, and polymers. Those materials have low optical nonlinear effect. One candidate material that can be used as a core material for optical waveguides and has a high optical nonlinear effect is Tin (IV) Oxide or SnO₂.

So as with tin which is widely available in Indonesia, where Indonesia is the second-largest tin producing country in the world after China [13]. So far, the tin industry in Indonesia has become an export commodity with positive prospects. Therefore, the tin industry will be very profitable if it can
be processed optimally into tin oxide (SnO₂), especially as a development of new, renewable materials for the telecommunications industry with various applications such as sensor materials [14], lithium battery anode materials [15], laser materials [16], gas humidity sensor devices, solar cells, light-emitting diodes [17], and many other applications. These wide and various applications cannot be separated from the advantages of the material properties of SnO₂, namely its high refractive index (2.006-2.486), high conductivity (~ 10³ Ω cm) -1, wide bandgap (≥ 3.6eV), [18-20] and its high optical nonlinearity (3.8 × 10-12 esu) [21]. Nanometer-sized SnO₂ material can also be used in optical device applications such as power dividers, directional couplers, and splitters as basic components in integrated optics.

The initial results of the waveguide research that the researchers conducted resulted in output in the form of two intensity image patterns, with the mode values on the output following the results of the intensity pattern of the waveguide. This result was consistent with the study of the optical power output of the waveguide simulated using the Eigen-Mode Propagation technique implemented with COMSOL and optimized by the 3D FD-BPM method [22]. The output for the waveguide design of this study had a Y-branch geometry; the wavelength used in the characterization process was 632 nm from the He-Ne laser. Also, the use of nanometer-sized SnO₂ material as the core of an optical waveguide could divide light well. This result was in accordance with the results of research conducted by Cao which showed that the amount of power used for the Y-branch in the light distribution process was not more than 0.85 mW and the coupling process time for both the Y-branch and Mach-Zehnder structures fluctuated between 0.8 ms and 0.2 ms [23].

This paper will discuss the research results on optical waveguides using SnO₂ semiconductor material as the core, PMMA material as substrate and cladding, fabrication using simple laser cutting to get a pattern of Y-branch channel with the core material is nanometer-sized SnO₂. The fabrication method is relatively simple and inexpensive, without the need for controlled room facilities such as cleanrooms or other complex supporting equipment. The independent variable in this study is the branch angle of the waveguide which later affects the coupling ratio and optical power. The advantages of a device with this structure are it also has an optimum optical power output with a small level of losses, a high tolerance for fabrication, and a good balance of power. This waveguide structure is made based on the principle of sharing the light intensity with the aim of passive optical device applications such as directional couplers, beam splitters, and power splitters.

2. Method
2.1. Materials
Acrylic/poly ( methyl methacrylate) in the form of cast acrylic sheet is produced by Marga Cipta, while ethyl cellulose is produced by Sigma Aldrich-USA and isopropanol (J.T Baker). Material SnO₂ nanopowder is <100nm particle size with the code 1002099194 (Sigma Aldrich. USA). Binder and other solvents were obtained commercially and used as received.

2.2. Acrylic Substrate Preparation
Acrylic/poly ( methyl methacrylate) or also known as PMMA in the form of cast acrylic sheet (produced by Marga Cipta) was chosen as a substrate because it has good mechanical properties such as tensile, bending, and compression. Polymethyl methacrylate (PMMA) is strong and has thermal stability better than PVC as a medium or substrate in waveguide fabrication. In addition, this material has good dielectric properties and electrical insulation, and also has excellent resistance to scratching (engraving). Acrylic material with a thickness of 2 mm was cut to the size of the waveguide pattern (design). The Y-branch waveguide was designed according to the length of the input arm and the design output. The fabricated size and pattern of the waveguide used Corel-Draw. Acrylic cutting was executed using a laser cutter. The purpose of cutting acrylic using this method was to make it more precise and straight. The fabricated size and pattern of the waveguide were formed through the engraving process (laser engraving). This process was similar to a laser cutter, except that the power used in the engraving process is not as large as on the cutting time, so the engraved substrate was not cut. In general, the stages in the research can be described in Figure 1.
Figure 1. Research Flow Chart

2.3. Preparation of A Solution of Tin Oxide
The preparation of the solution was carried out by mixing the solvent and binder, where ethyl cellulose ([C₆H₇O₂(OH)₃n(OC₂H₅)ₙ]ₓ) acted as a binder and isopropanol as a solvent. The preparation of this solution was performed by dissolving 0.13 grams of ethyl cellulose and 3 ml of isopropanol first, then stirred using a magnetic stirrer hotplate with a heating temperature of 50°C for 1 hour. The heating process was carried out so that the solution was more easily mixed, provided that the heating temperature was below the melting point of ethyl cellulose and isopropanol (160°-210°C). Meanwhile, the length of time for stirring aimed to make the binder and solvent mixed perfectly without any small lumps in the solution. After the solution of binder and solvent was completely mixed, 0.25 gram of nanopowder was added. Later, the mixed solution was stirred for 2 hours with a heating temperature of 50°C using a magnetic stirrer hotplate. The duration of stirring-time aimed to dissolve the powder, and the solute-solvent could not be differentiated. The solution was covered by aluminium foil and cooled for 24 hours. When it had turned into a gel, the solution was ready to be deposited on the acrylic substrate.

2.4. Measurement of Port Output on the Waveguide Y-Branch.
Characterization of the Y-branch waveguide was performed by measuring the output 01 and output 02 of the Y-branch waveguide shown in Figure 2. The He Ne laser beam was then inserted into the syringe hole wherein the waves would propagate into the Y-branch waveguide. The laser beam output was photographed from the fabricated cross-section of the Y-branch. The Image-J software processed output intensity until the intensity distribution pattern of the waveguide was obtained.
3. Results and Discussion

3.1. Measurement Result Data

The data of the Y-branch waveguide channel width measurement results are shown in Table 1.

| Type | Width input channels (mm) | Output channel width 1 (mm) | Output channel width 2 (mm) | Depth waveguide (mm) |
|------|---------------------------|-----------------------------|-----------------------------|----------------------|
| I    | 0.0510 ± 0.01             | 0.0515 ± 0.01               | 0.0506 ± 0.01               | 2.0 ± 0.01           |
| II   | 0.0495 ± 0.01             | 0.0495 ± 0.01               | 0.0494 ± 0.01               | 2.0 ± 0.01           |
| III  | 0.0541 ± 0.01             | 0.0571 ± 0.01               | 0.0545 ± 0.01               | 2.0 ± 0.01           |

Characterization process of Y-branch waveguides was undertaken in laboratories at the darkroom condition to minimize the light effect other than the source used. The manufactured HeNe laser waveguides had a wavelength of 632.8 nm. The waveguides characterization process was started by taking a cross-section of Y-branch channels that had been created in Table 2.

| Type | The intensity of output channel 1 (%) | The intensity of output channel 2 (%) | Losses (%) |
|------|---------------------------------------|---------------------------------------|------------|
| I    | 40.4 ± 0.1                            | 56.9 ± 0.1                            | 27.0 ± 0.1 |
| II   | 29.7 ± 0.1                            | 41.1 ± 0.1                            | 29.3 ± 0.1 |
| III  | 33.9 ± 0.1                            | 27.8 ± 0.1                            | 38.2 ± 0.1 |

3.2. Discussion

The process to engrave (engrave) acrylic material using a CO$_2$ laser was hold by focusing the laser beam so that it had high energy into a smaller place (laser needle) with a laser diameter of 0.006 inches. The heat energy generated by the laser could vaporize acrylic material with a size of 30 mm x 10 mm x 2 mm. CO$_2$ gas was used to remove the evaporating material from the acrylic out of the engraving/scratches. Light energy was applied directly to the acrylic area to form an engraving according to the pattern and size dimensions of the Y-branch waveguide.

After the engraved guiding pattern is produced, width measurements are made on the Y-branch waveguide channel using a microscope equipped with a camera and micrometer and connected to a
computer. This characterization process is described elsewhere [24]. The results of the gap width in the input and output channels of the Y-shaped waveguide on average 0.051 mm with a depth of 2 mm, are shown in Table 1. The fabrication of an optical waveguide in the form of a Y-branch could guide laser light quite well. The waves propagation in waveguide was restrained due to the total reflection of the waveguide walls. Hence the propagation in waveguide could roughly be described as “zigzags” between the waveguide walls [25]. Likewise, this mode could be guided because the process of guiding light in a waveguide was near related to optical light phenomena in the boundary plane between the two mediums.

From the results of the Y-branch Type I optical waveguide propagation, it was found that the power value and its losses were relatively small compared to other forms of Y-branch waveguide. In this channel, the output was almost the same for the two outputs, or in other words, the guidance of the guided light distribution on the canal could be evenly divided, namely 40.4% and 56.9%. The percentage value of the output intensity of each channel Y-branch optical waveguide were mentioned in Table 2. Table 2 describes that the performance of the proposed Y-branch waveguide as a power divider is quite good. This was also comparable to previous work of Kassim et al [26]. Thus, the Y-branch Type I waveguide was very suitable for passive optical device system applications because it could load more optical components that were integrated into the optical circuit.

4. Conclusions
This study can produce a Y branch waveguide based on SnO\textsubscript{2} as a core with substrate and cladding made of acrylic and PMMA. The design that has been made shows that the Y branch waveguide with the CO\textsubscript{2} laser cutting method can transmit light propagation in the waveguide optimally with small losses. Thus, the Y branch waveguide as a power divider can be integrated as a passive optical device.

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