A Study of an Antenna Coupled Optical Y Branch and Its Applications(アンテナ結合型光Y分岐とその応用に関する研究)

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論　文　内　容　要　旨

Abstract: A new type of an efficient and optimum antenna coupled Y branch is proposed. Detaild analysis of the proposed Y branch in various three dimensional structures is carried out. The proposed Y branch is actually fabricated using Ti−diffused $LiNbO_3$ and the characteristics are experimentally verified. As an applicaton, an integrated optical switch of the Mach−Zehnder type, using the proposed Y branch structure as the power divider (and power combiner) is proposed and analyzed. The switch is fabricated using Ti−diffused $LiNbO_3$ and is experimentally verified.

Introduction:

Single mode Y branch waveguides are key elements in the realization of various integrated optical systems. They are used as optical power dividers or 3 dB couplers in switches of the Mach−Zehnder (M−Z) interferometer type. One disadvantage of this kind of switch, with the conventional branch, is that there is a need for extra bending or curved elements at the connection of the 3−dB coupler part and the phase shifter part, which increases the overall size and the insertion loss of the device. The various other systems that use the Y branch waveguides include, multiplexers for wavelength division multiplexing systems, heterodyne detection systems, image processing and signal processing systems and sensor applications. The main requirements of an optimum Y branch, include, low loss, compactness or small size, ease of fabrication, and without a need for tuning etc..

In order to realize an efficient and optimum Y branch structure, i) with low branching loss, ii) which is of compact size, iii) which does not need extra bending or curved elements when used as a 3 −dB coupler in M−Z type switches (which results in low insertion loss and compact size), iv) which is free from critical fabrication requirements, which can be used, not only as a 3 −dB coupler in M−Z type switches, but also as an individual element in various integrated optical systems, a new type of an antenna coupled Y branch is proposed. The detailed analysis of the proposed Y branch is carried out.

Principle of operation of the proposed Y branch:

Fig. 1 shows the two dimensional (2 D) structure of the proposed structure. This structure uses the principle of radiation modes and can be explained as follows. The launching waveguide is truncated at $z=0$, and the wave diffuses into the $\pm x$ directions. The tapered portion of the branching waveguides relaunches the " once radiated " wave into the two parallel output waveguides. As the two output waveguides are parallel, the phase front at $z=L$ is required to be nearly perpendicular to the z axis. This " phase control " is achieved by reducing the outside refractive index n_3 from n_1. As a result an efficient Y branch structure with low loss and compact size is achieved.

Analysis of the Y branch:

Propagating Beam Method (PBM) is used in the analysis of the Y branch. The mode eigenfunctions of the input and the output waveguides of the Y branch structure are calculated. The input end of the Y branch is excited by the eigenmode and the field at the output end is determined by PBM and the branching loss is calculated by the overlap integral. Fig. 2 shows the calculated branching loss of the 2 D structure of Fig. 1. At the optimum condition (ie., $n_1=2.2$, $n_2=2.20196$, $n_3=2.19902$, $W=7\ \mu m$, $\lambda=1.3\ \mu m$, $\theta=0.7°$) the branching loss is 0.07dB, which is lower than that of the existing Y branch structures.

For the first time, a three dimensional (3 D) PBM of a ridge type waveguide is successfully attempted, which was not possible till now due to the problem of a large refractive index difference between the ridge guide and the cover region (which is usually air). An approximation is used and a suitable method is obtained. By analyzing various ridge type structures using PBM, the validity of the new method is confirmed. To minimize the radiation loss at the transition region of the Y branch (when a 3 D structure is considered), a ridge type Y branch structure (Fig. 3) is proposed and analyzed. Fig. 4 shows the branching loss of the ridge type Y branch structure. The branching loss of the corresponding 2 D structure, using the effective index method, is also calculated. It is observed that the 2 D and 3 D calculations agree closely.

It was further observed that the radiation into substrate increases, at the transition region of the ride structure (Fig. 3), as the refractive index n_3, is reduced from n_1 (that of the substrate). As a result, the branching loss of the proposed structure is not decreasing, although the value n_3 is reduced (as observed from the 2 D analysis). In order to minimize this kind of loss and hence, to achieve an optimum antenna coupled Y branch structure with a minimum branching loss, a modified 3 −D embedded waveguide structure as shown in Fig. 5, is proposed and is analyzed. A branching loss of 0.07dB (which is same that for the case of a 2 D structure) is achieved.

The 3 D analysis of a diffused Y branch structure (a Ti−diffused $LiNbO_3$ structure) is also carried out.

Experimental verification of the Y branch struture:

To verify the theoretical results of the proposed Y branch structure, the Y branch structure is fabricated using Ti−diffused $LiNbO_3$ and the branching loss is experimentally verified. A low branching loss Y branch structure (0.4dB) is realized. The fabrication process is shown in Fig. 6, and the near field pattern of the fabricated sample is shown in Fig. 7. Thus the performance of the proposed Y branch sturcture is experimentally confirmed.

A method to reduce the refractive index on the outer sides of the branching waveguides of the proposed Y branch:

In the analysis of the proposed Y branch structure, it is proved that the branching loss will be reduced if the refractive index on the outer sides of the branching waveguides (" n_3 " region in Fig. 1) is reduced. In order to verify it experimentally, a method is described. In this method, the refractive index of the " n_3 " region is relatively decreased, by increasing the refractive index on other parts of the Y branch. This achieved by coating a layer of Al_2O_3 on all parts of the Y branch except the " n_3 " region. The necessary sample is fabricated and a reduction in branching loss of 0.2 dB for TE mode and 0.4 dB for TM mode is achieved.

An application−a M−Z interferometer type switch:

As an application of the proposed Y branch structure, a switch of the Mach−Zehnder interferometer type (Fig. 8), which uses the proposed Y branch structure as a power divider and combiner is proposed and is analyzed. A switch using a Ti−diffused $LiNbO_3$ is fabricated and the switching experiment is carried out. Fig. 9 shows the measured and calculated response of the fabricated switch. Both these curves agree closely.

One disadbantage of this switch is the poor extinction ratio at the initial minima. The reason is due to the fact that the gap between the two arms of the phase shifter part is narrow, and the there is coupling between them. The various existing methods are described to avoid this problem and to achieve an optimum switch configuration.

Conclusion:

In this research work, a new type of an antenna coupled Y branch is proposed. It has the following advantage,

i) low branching loss,

ii) which does not need extra bending or curved elements when used as a power divider or 3dB coupler in Mach−Zehnder type switches, resulting in low insertion loss,

iii) small and compact size,

iv) easy to fabricate, ie., without critical fabrication reqirements.

This structure was analyzed using the two dimensionl PBM. For the first time, three dimensional PBM of a ridge type waveguide structure was successfully attempted. The proposed structure was analyzed in a ridge type configuration and in a modified embeddedtype structure using three dimensional PBM. The three dimensional analysis of the diffused Y branch structure (Ti−diffused $LiNbO_3$) is also carried out.

The proposed structure was actually fabricated using Ti diffused $LiNbO_3$ and the branching loss was experimentally verified. A method to reduce, relatively, the refractive index on the outer sides of the branching waveguides of the Y branch structure is also described.

As an application, a Y branch interferometer (Mach−Zehnder) type switch using the proposed structure as a power divider or 3dB coupler was also proposed. The switch configuration was analyzed theoretically and was fabricated using Ti diffused $LiNbO_3$ and the switching experiment was carried out. The detailed discussion of the experimental and theoretical characteristics were also given.

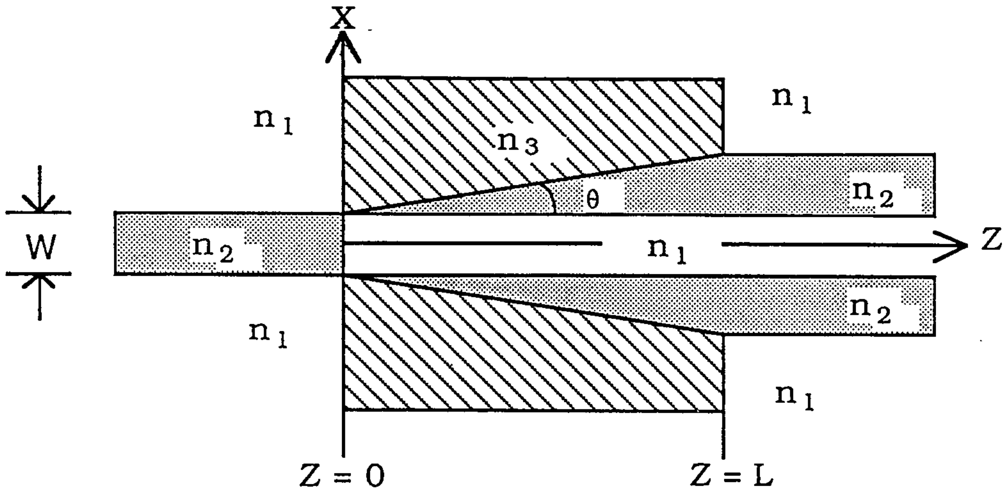

Fig. 1. Proposed Y-branch structure.

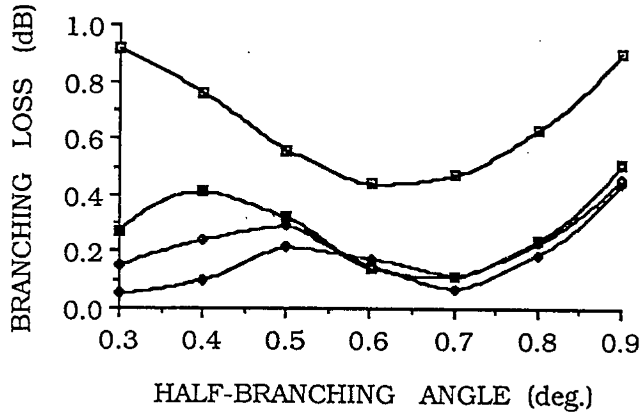

Fig. 2. Branching loss of the Y branch for various n_3 values.

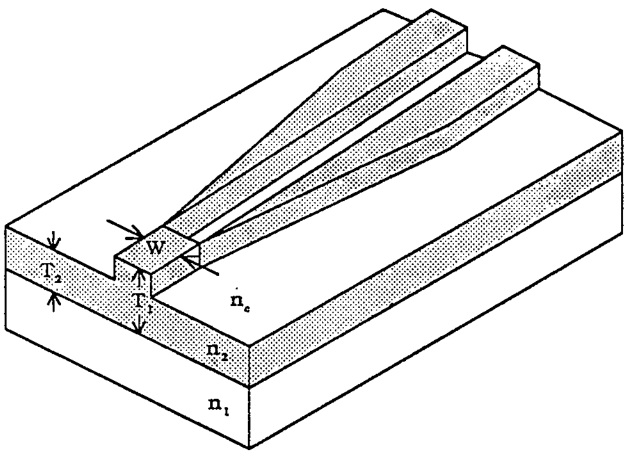

Fig. 3. The 3-D ridge type Y-branch.

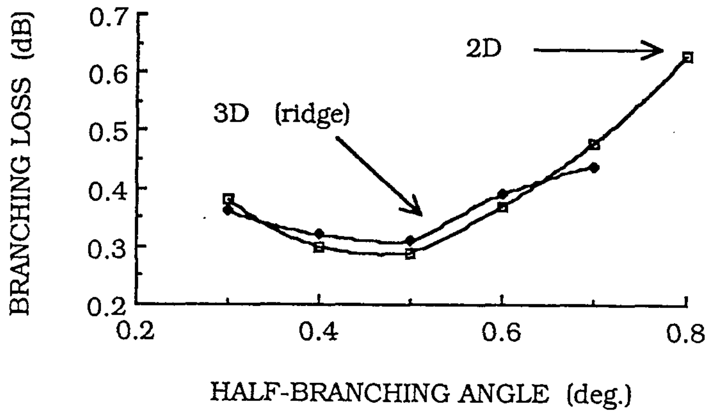

Fig. 4. Branching loss of the 3D ridge structure.

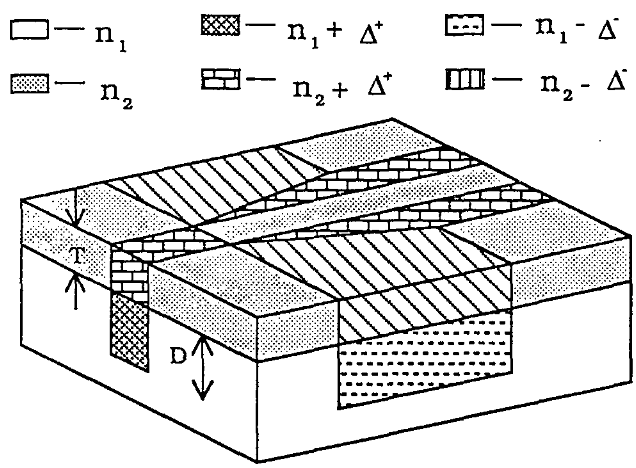

Fig. 5. The modified embedded type Y-branch.

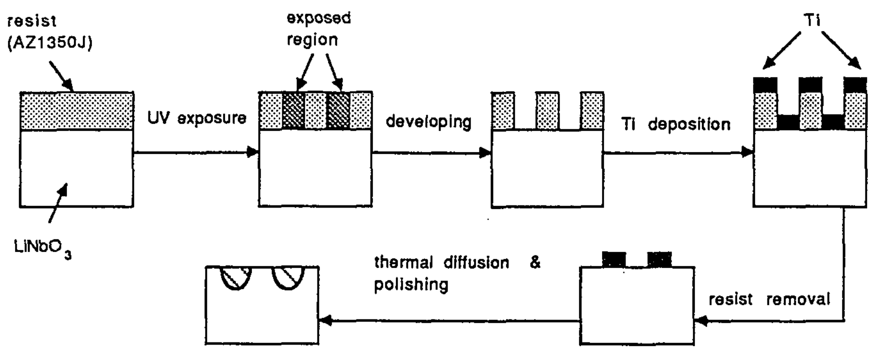

Fig. 6. Fabrication process of the Y branch.

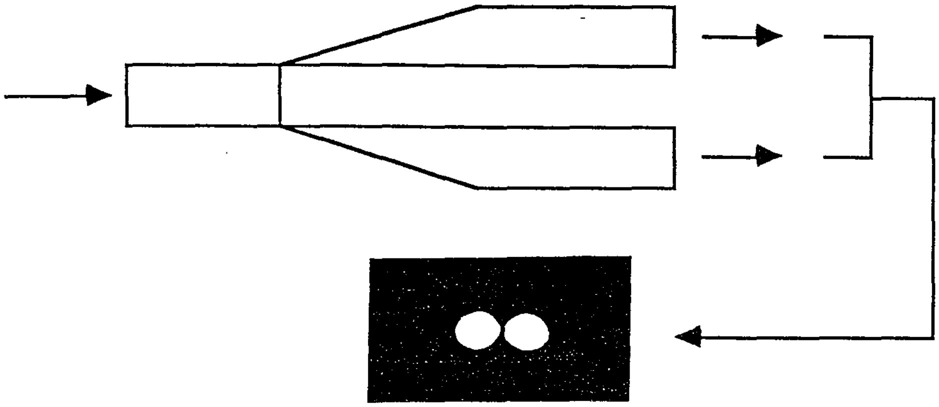

Fig. 7. Near field pattern of the fabricated sample.

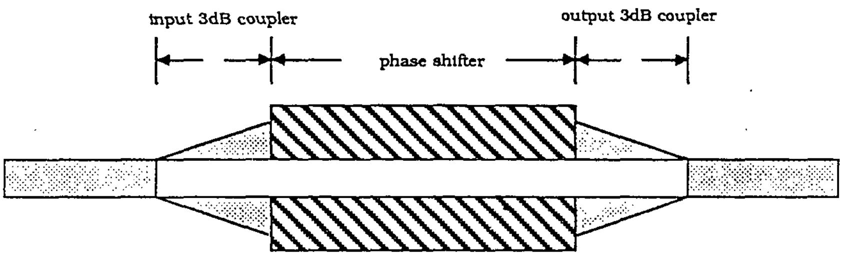

Fig. 8. schematic of the proposed M-Z type switch.

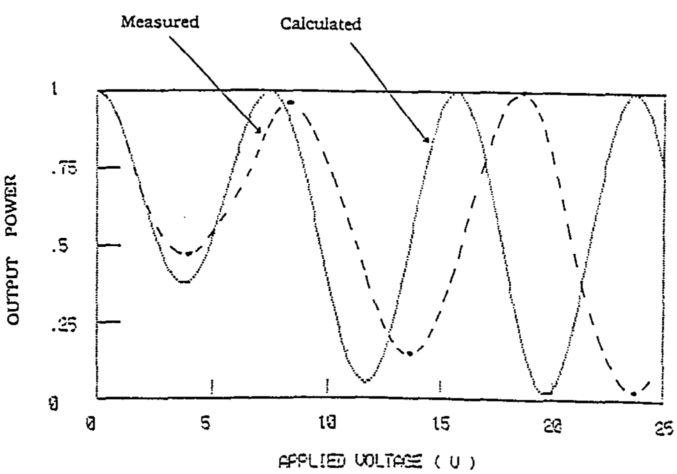

Fig. 9. The measured and calculated response of the fabricated switch.

審 査 結 果 の 要 旨

近年，光集積回路技術は，通信・計測・情報の分野において目覚ましい発展をとげつつあり，光デバイスの小型化高性能化はその基礎技術として重要である。とりわけ分岐・合流回路は最も基本的な素子の一つであり応用範囲も広い。本論文は，放射波を利用した新しい原理に基づくＹ分岐導波路とその応用デバイスについて理論と実験の両面から行った研究をまとめたもので全編７章よりなる。

第１章は緒論である。

第２章では，放射波の波面制御の可能性について論じ，従来光集積回路では使われることの少なかった放射波を活用した小型高性能分岐素子の得られることを明らかにしている。即ち，入射側の導波路を伝搬してきた導波光を一旦基板中に放射すると，波面は平面から球面へと移行し界分布は広がる。放射波領域に平行な２本のテーパ導波路を差し込んだ構造（アンテナ結合型と呼ぶ）とし，更にテーパ導波路の外側領域で波の位相速度を上昇させれば短い距離で２本の平行な導波路に放射光を集め得ることを見出した。これは優れた知見である。

第３章では，素子の解析に用いる計算法ＰＢＭ（Propagating Beam Method)をのべ，リッジ型光導波路に適用可能な形に拡張した計算法について詳述している。これによりリッジ型及び埋込型Ｙ分岐素子を設計し，分岐損失0.1dB以下となしうることを示している。また，拡散型光導波路を用いたＹ分岐素子についても設計法を述べている。

第４章では，$LiNbO_3$ 結晶基板にTiを拡散した光導波路を用いて実験的検討を行い，テーパ角１度，光波長1.3μm でＴＥ，ＴＭモードに対して分岐損失0.4dB なる特性を得ている。更にテーパ導波路外側の屈折率を低減化した波面制御素子を試作し，分岐損失が低減化することを確認している。これらは優れた成果である。

第５章では，アンテナ結合型Ｙ分岐素子と平行な二つの導波路とを用いたマッハツェンダー型光スイッチを提案し，特性の解析を行っている。

第６章では，提案した光スイッチの作製法と測定結果について述べている。Ｔｉ拡散$LiNbO_3$光導波路を用いた実験により，本論文のＹ分岐はスイッチ素子の小型化高性能化無調整化に有効であり，再現性が良いことを示した。これらは実用上重要な知見である。

第７章は結論である。

以上要するに本論文は，放射波制御技術を利用した新しいＹ分岐素子を提案し，解析と実験によりその有用性を明らかにしたもので，光電子工学の発展に寄与するところが少なくない。

よって，本論文は工学博士の学位論文として合格と認める。