Compact Polymeric Optical Attenuator Using Laser Writing Asymmetric Y-Junction

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Abstract

We have proposed and demonstrated a wide-angle thermooptic variable optical attenuator using a new type of truncated asymmetric Y-branch waveguide in polymers. The asymmetric parameters in the truncated zone and also the asymmetric waveguide widths of the branch depend on its cross-talk (CT), attenuation efficiency and the length of the device or the packing density. An analysis for the optimum phase matching at the branching zone is performed to improve the transmission efficiency. The attenuation efficiency of this structure with variation of the device parameters is studied. In the passive state the simulated cross-talk is obtained ~ –38dB at branching angle 2A=1°. It is shown that the length of each attenuator is ~ 1.3 mm which is about 6.5 times less than that of the attenuator using a normal Y-junction. The structure also shows that the wanted power in the wider output arm can be made maximum at the phase matching between the inner and the outer paths of bending and also considering the optimum parameters of the structure. A focused argon-ion laser beam (\lambda=351nm) was used to polymerize acrylate monomer for patterning the core waveguide. The Gaussian shaped core with uniform refractive index profile produces an equivalent rib structure with a single-mode channel waveguide even for high-index difference core and the cladding. The experimental results of relative output power in the wider arm of the proposed structure without trench versus electrical power consumption of the heater and the corresponding simulated results are shown. The simulated result of the structure with a trench shows the improvement of electric power consumption.

Keywords: Integrated Optics, optical attenuator, polymer rib waveguide, thermooptic effect, laser - writing

1. Introduction

The voltage controlled waveguide type optical attenuator has attracted much attention because it can be used to keep on line channel output powers constant irrespective of the change in input power \cite{1,2}. Actually, there are gain fluctuations in an EDFA with wavelength and the output power variation in 2X2 coupler, in add/drop nodes, and the waveguide devices produced by the change of polarization, for which it requires to equalize the channel powers at the output \cite{3}. In dense wavelength-division multiplexed (DWDM) systems application, there must be need of optical attenuators array with variable gains \cite{4,5}. A small size with low cross-talk, reduced voltage-length product with linear output power variation, and low power consumption for each attenuator will be the key issue for the implementation of this array. An asymmetric Y-junction can be used as attenuators or digital optical switches (DOSs) when the output guides have the effective refractive index difference, and its length can be made low compared to that of a directional coupler \cite{6-8}. Furthermore, they are fairly insensitive to fabrication tolerance because precise adjustment of the propagation constant is not required. The thermooptic variable attenuator using an asymmetric normal Y-branch (NYB) waveguide in polymer with heater size of 7.5 mm x 10 mm was demonstrated obtaining the maximum cross-talk of ~ 25dB\cite{1}.

Actually, this NYB structure used as a mode splitter suffer from severe radiation losses \cite{6}, particularly when full branching angle 2A is larger than 0.3°. This limits the packing density of the integrated optical devices. Different Y-branch structures \cite{9,10} aiming reduction of radiation loss at a much larger branching angle have been proposed. Again, the polymer waveguide technology is attractive for many advantages, including a large thermooptical coefficient and low thermal conductivity, and also simple for fabrication process \cite{11,12}. It has already passed electrical overstress tests according to Bellcore standards.

In this paper, a compact thermooptic polymeric attenuator using a truncated asymmetric Y-junction and a rib type waveguide structure operated by a laser beam to polymerize monomer solution for
pattern the core waveguide, is presented. A mixture of two intermiscible acrylate monomers, and also the reliable with thermal stable polymers are used here for the cladding and the core of the waveguides. The inner walls of the core around the branching zone are made to bifurcate and filled with cladding refractive index $n_2$. The variable waveguide widths required along the propagation length for this structure are obtained from on-line controlling of the laser beam. For this wide-angle branches, the proper shaping in the truncated zone improves crosstalk and for the optimum condition of the junction parameters. The simulated crosstalk is obtained ~ -38 dB at $2A=1^\circ$ without application of heating power. The measured cross-talk in the passive state was obtained ~ -30dB with polarization dependent loss less than 0.6dB. The performance of the attenuator with the change of refractive index obtained by varying voltage to the heater in the outer arm of the junction, are shown. The experimental results of relative optical output power in the wider arm versus electrical power consumption of the heater of the proposed structure without trench almost agree with the simulated results.

2. Proposed Structure

In the proposed structure, as shown in Fig.1(a), it consists a asymmetric truncated Y-branch (TYB) structure where the inner walls of the core around the branching zone of the truncated structure are made to bifurcate and filled with cladding refractive index $n_2$. There are asymmetric gaps ($G_1$&$G_2$) at the truncated zone, and at a reduced truncated-structural angles ($B_1&B_2$) compared to branching angle (2A) with asymmetric output waveguide widths (2D1&2D2). The asymmetric output guide arms can be obtained by making $D_1 > D_2$ (wanted power in D2 arm) and keeping the core guide index $n_1$ for both the arms same $6.10$. The operation of the device follows by obtaining maximum wanted output power in the wider arm ($P_w$) of the branch due to asymmetry in the waveguide width, when the unwanted power in the narrow arm is $P_n$. Then the cross-talk CT = ($P_w$/P_n) will be minimum when there is no electrical power supplied to the heater. When the wider arm is heated by applied electric power, the effective index of the wider arm will be decreased due to negative temperature coefficient of polymer and optical power in this arm will be attenuated and some portion of the input optical power is transferred to the narrow arm following the increase of CT. We have studied the transmission characteristics to obtain minimum CT without electrical power to the heater and also the attenuation efficiency with the decrease of effective index in the wider arm when heated.

3. Phase Matching in Wide-Angle Structure

The hatched area around the branching zone of Fig1(a) being made with cladding index $n_2$ is actually the core index $n_1$ in NYB structure. The lower cladding index at the branching actually compensates the phase difference caused by bending, which is high for higher angle branches. The junction introducing lower cladding index in the truncated zone actually increases the attenuator branching angle with higher efficiency. The propagating time around the line $L_i$ is $L_i n_i/c$ in the core and $L_i n_2/c$ in the cladding, $c$ being the velocity of light in free space. For the phase difference $\delta\phi$ (pd) due to change of refractive index to be equal to the phase change $\delta\phi$ (pd) due to path difference caused by bending, when the CT of the attenuator becomes minimum and efficiency is maximum. An expression of phase matching condition can be developed with the following expression

$$n_{eff}(\Delta l_{max} + N \lambda) = (n_i - n_2)(D_i + G_i)/\sin(A - B)$$  \hspace{1cm} (1)

where $\beta = k_o$, $n_{eff}$ is the propagation constant of the guided mode and $N = 0,1,2, \ldots$, $\Delta l_{max} = 4D_1 \tan B$, $i =1$ and 2 for the narrower and the wider arms, respectively, and $N > 1$ due to small value of $A$ for fulfilling the condition $2A << \Delta \beta/\gamma$. $\Delta \beta$ is the difference in propagation constant for the modes of the guiding regions and $\gamma$ represents the transverse component of the wave vector in the central cladding region $m$. Thus the asymmetric Y-branching waveguide with shallow taper acts as a mode splitter in which a mode would choose the output arm with an effective index closest to the effective index of the input arm. It is clear from equation (1) that for the requirement of minimum cross-talk and low loss system, $G_1$ will be greater than $G_2$ for the asymmetric guide widths $D_1 < D_2$. Of course, in the proposed truncated structure phase matching is not considered in the core region $n_1$ of the branching waveguides. Actually, the effective length $L_{eff}$ in the truncated zone will be less than the calculated value of $L_i$. Fig. 2 shows the simulated results, based on two-dimensional finite difference beam propagation method combined the effective index method, following the decrease of cross-talk CT with the increase of difference of the output guide widths $\Delta D = (D_2 - D_1)$ for three values of $\Delta n$, effective index difference of the rib structure, with the fixed values of $G_2 = 0.02 \mu m$, $G_1 = 0.1 \mu m$ and $D_2 = D = 4.3 \mu m$ at $A = 0.5^\circ$. Under
Fig 1 (a) Proposed Y-branch structure for a compact optical attenuator.

Fig 1 (b) Cross-section of Fig. 1(a) at X’X with Gaussian rib waveguide.

Fig 1 (c) Cross-section of Fig. 1(a) at X’X with equivalent rectangular rib waveguide.
this condition the phase matching occurs following equation (1) when ΔD=2.0µm, Δn=0.0035, B₁=0.3286° and B₂=0.2737°. The figure shows that CT increases for the other values of Δn under the mismatch condition when δd (pd) ≠ δϕ (ri). There is a maximum value of ΔDₘₐₓ for each value of Δn when CT is minimum. During propagation after branching the optical power will be guided more in the wider arm and increases with the increase of the propagation distance.

![Graph showing CT versus difference of asymmetric waveguide widths of Y-branch attenuator.](image)

**Fig 2** Simulated cross-talk (CT) versus difference of asymmetric waveguide widths of Y-branch attenuator.

### 4. Length of the Attenuator

It is important to design low loss smaller length mode splitter for compact attenuator in which it is required to know the interguide gap hₒ(z) along the direction of propagation where there is the peak value of the coupling coefficient Cₒ between the output guides of the branch \(^3\). At hₒ(z) there is the peak value of mode coupling γₒ when hₒ(z)=f(γₒ) and γₒ can be written as

\[
gₒ = Cₒ p (Aₒ) / |δβₒ| \tag{2}
\]

where Aₒ is the local half branching angle of the junction and \(Δβₒ = βₒ - β₁\), (βₒ or β₁) is the propagation coefficient of each mode of the output guides. Actually, the index asymmetry Δn = (Δβₒ / 2π) increases with the increase of difference of the waveguide widths ΔD = D₂-D₁, difference of gap widths ΔG = G₁-G₂ and also with the change of truncated-structural angles B₁ and hence hₒ(z) decreases with the increase of both ΔD and ΔG. Thus the length of the device decreases with the increase of ΔD and ΔG for a fixed value of B₁. However, changing B along the direction of propagation Z improves CT \(^4\). It is clear from Fig.1(a) that \(Δβ\) is more for the structure TYB compared to that of the structure NYB, and thus the length of the TYB structure used for an attenuator is less and the device structure will be compact. The CT for the asymmetric structure can be obtained knowing the field ratio R = A₁/A₂, where A₁ and A₂ are the amplitudes of each mode and CT can be expressed as

\[
CT = R² / (1 + R²) \tag{3}
\]

The simulated BPM result of CT versus Z at θ=0.5° is shown in Fig.3 where CT decreases with Z for different values D₁ and the fixed values of B₁=0.3286°, B₂=0.2737°, G₁=0.1 and G₂=0.002 µm, D₂=4.3 µm, and Δn=0.0035. The figure shows the improvement of CT with the increase of ΔD at a given value of Z. It can also be shown that CT decreases with the increase of ΔG keeping the other values unchanged. Thus it is clear that the length of the splitter will be reduced with the increase of ΔD and ΔG, but up to their optimum values. The shape of the truncated structure and by reducing A₁ at the peak value of hₒ(z), or optimizing the angle B₁ or introducing variable B₁ along Z, the length of the structure can further be made minimum. Fig.4 shows a typical array of attenuator using TYS structure after fiber amplifier and splitter. The variable power of different wavelengths can be made uniform
after the attenuators by controlling the temperature of the heater placed in the wider arm of each attenuator. The length of each attenuator is ~ 1.3 mm considering only the attenuation unit, which is about 6.5 times less than that the attenuator using a normal Y-junction.

![Graph showing cross-talk (CT) versus propagation distance Z of Y-branch attenuator for different values of narrower arm width D₁.](image)

**Fig 3** Cross-talk (CT) versus propagation distance Z of Y-branch attenuator for different values of narrower arm width D₁.

**Fig 4** Array of compact attenuators with heater.

**5. Fabrication of Polymeric Attenuator by Laser Writing**

We fabricated the rib waveguides by using photo-chemically curable acrylate monomers. After cleaning the substrate the lower cladding layer of film thickness ~5μm and refractive index n₂=1.49 at λ=1.5 μm was deposited on it by spin coating the monomer solution. This cladding layer was then polymerized by thermal curing to be resistant to the core solvents and to provide good adhesion to the core layer. We followed the process of partial polymerization by controlling the temperature and time
to avoid birefringence. Then the core layer was spun on the partially polymerized cladding layer for which the control of its thickness refractive index are important for a single mode rib structure. We used two intermiscible acrylate monomers and by mixing them we obtained high-index core $n_1 = 1.55$ at $\lambda = 1.5 \, \mu m$ of the waveguide. The required core-index $n_1$ will be less of the waveguide with SiO$_2$ as lower cladding with the same upper cladding index. We then patterned the core waveguide by focusing the argon-ion laser beam with the laser direct-writing apparatus. Laser writing microtechnique that differs from a conventional mask-based photolithographic system, affords considerable latitude in focusing and controlling the power level and scanning speed for fabricating novel structures without affecting the surrounding area. Laser beam produces generally the core a Gaussian shape with a uniform refractive index profile because of the Gaussian intensity profile of the laser beam. An oversized rib waveguide structure was produced by controlling the etching time after complete of polymerization. Fig.1 (b) shows the cross-section of the asymmetric Y-junction in the truncated zone having equivalent Gaussian rib widths $2D_{1t}$ and $2D_{2t}$ for the narrow and wider arms, respectively. Outside the truncated zone the Gaussian rib widths are $2D_1$ and $2D_2$ where as the width before the junction is $2D$. Fig.1 (c) shows the equivalent rib heights $T_{e1}$ and $T_{e2}$ with widths $2D_{e1}$ and $2D_{e2}$ for the narrow and wider arms, respectively, and the slab height $T_s$. For a single-mode waveguide in the stem region before the junction the equivalent dimensions of the rib $2D_e$, and $T_e$ and $T_s$ need to fulfill the following equations: 

$$\frac{T_e}{(T_e + T_s)} \geq 0.5$$

$$2D_e \left(\frac{T_e}{T_e + T_s}\right) \leq 0.3 + \frac{T_e}{\left(1 - \frac{T_e}{(T_e + T_s)}\right)^{3/2}}$$

Under this condition, higher-order modes in the central rib region due to large cross sections or high-index contrast between the core and cladding film will be coupled to the slab section, but leaks out during propagation because the effective index of the fundamental slab mode becomes higher than that of any higher-order modes in the rib region. We fabricated a rib-wave guide structure as shown in Fig.1 in which $T_p = 10 \, \mu m$, the maximum height in the central rib section of the core over the lower cladding of thickness $\sim 6 \, \mu m$, was controlled by dwell time $t_d = 25 \, ms$ and $P_{in} = 26 \, \mu W$ when the width of the focused laser beam $2R$, at 1/e point is equal to $7.3 \, \mu m$. $2D_e$ and $T_e$ will be obtained easily as $\sim 8.0$ and $\sim 4.6 \, \mu m$, respectively. The thickness of the slab of core $T_s = 5 \, \mu m$ was obtained by control of etch time. This dimension of oversized rib structure matches the cross section of the waveguide to couple a single-mode fiber to increase the coupling efficiency. Following Fig.1 the laser writing apparatus was on-line controlled for the dimension of the core along the length of propagation simply by adjusting the XYZ stages. Finally, the top cladding layer of refractive $n_2$ and thickness $\sim 7 \, \mu m$ of a monomer solution was spin coated upon the Gaussian-shaped core and then cured by UV light. The measured cross-talk in the passive state of this asymmetric Y-junction fabricated at optimum condition of phase-matching is $\sim 30 \, dB$ with polarization loss less than $0.6 \, dB$. The deviation of this value from its simulated result is due to variation of the asymmetric junction parameters and mainly due to deviation of the optimum parameters in the truncated zone during fabrication by laser writing.

### 6. Attenuation Efficiency and Results

It is important to know the variation of wanted output optical power, $(P_w)_H$ in the wider arm of the attenuator with the change of refractive index $\Delta n$ of the core of the wider arm, obtained by changing the heating power of the heater. The relative wanted optical power $R_H$ variation with the heating power can be written as

$$R_H = \frac{(P_w)_H}{(P_w)_{H=0}}$$

where $(P_w)_{H=0}$ is the maximum optical power without heating power. Fig.5 shows the simulated plots of $R_H$ versus $\Delta n$ for three values of $B_1$, keeping fixed values of $B_2 = 0.2737^\circ$ when the other values are same as given in Fig.2. The attenuation efficiency increases with the decrease of $B_1$. To demonstrate the feasibility in implementing an attenuator based on our proposed structure, a metal electrode film of size...
L~1400, and W~9 µm was evaporated on the upper cladding layer of the wider arm. The distance from the centre of the junction to the starting of the heating element $L_g$ is kept < 400 µm, otherwise most of the power will be radiated out from the wider arm guide instead of coupling in the narrower arm guide of the junction and it was taken at ~100 µm. The optical power from the wider arm will be attenuated on application a dc voltage to the electrode when the power in the narrower arm will increase. Fig.6 shows the experimental results of relative output power $R_H$ in the wider arm versus electrical power consumption of the heater for the proposed structure without trench. The nature of variation of $R_H$ almost agrees with the simulated results as given in Fig.5. The simulated results of this structure with a trench having height $H=12$ and width $W=15$µm is also shown in Fig.5 by dotted line 18.

![Fig 5 Simulated plots of relative output power versus change of effective refractive index of wider arm core.](image)

![Fig 6 Optical output power versus heater power of the proposed Y-branch attenuator.](image)

7. Conclusion

We have proposed and demonstrated a compact thermo-optic variable optical attenuator using a truncated asymmetric Y-branch. The asymmetric parameters in the truncated zone and also the asymmetric waveguide widths are optimized to obtain low cross-talk (CT), higher attenuation efficiency and shorter length of the device to improve the packing density. The simulated cross-talk of ~ -38dB at branching angle $2A=1^\circ$ is found without heating. It is shown that the length of each attenuator is ~ 1.3 mm which is about 6.5 times less than that of the attenuator using a normal Y-
junction. A focused argon-ion laser beam (λ=351nm) was used to fabricate the device to polymerize monomer solution for patterning the core waveguide. An equivalent rib structure with a single-mode channel waveguide even for high-index difference core and the cladding was produced by the Gaussian intensity profile laser beam. At optimum condition of phase-matching the measured CT was ~ -30dB with polarization dependent loss less than 0.6dB. The higher value of CT from its simulated result is mainly due to deviation of the optimum parameters in the truncated zone during fabrication by laser-writing. The experimental results of relative optical output power in the wider arm versus electrical power consumption of the heater without trench almost agree with the simulated results.

References