Novel VOA Configuration using a Trapezoidal PLZT with 400-ns Response Speed and 1.5-dB Insertion Loss

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Abstract: A novel reflection type VOA with a trapezoid bar PLZT is proposed. The drive voltage can be reduced by minimizing the electrode gap. This VOA has realized a small V_π of a quarter of the conventional value or less. It is difficult to support a fast response and a low loss simultaneously. The VOA has overcome this difficulty by using the novel trapezoidal PLZT and has achieved a 400-ns response with a 27-V drive voltage and a 1.5-dB loss simultaneously.
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1. Introduction

A long-reach passive optical network (PON) system can allow us reduce costs and increase the number of subscribers. One promising method in this regard involves using optical level control equipment [1]. Optical packet switching system is one of the most effective systems for coping with the rapidly increasing traffic load. A burst-mode automatic gain control-erbium doped fiber amplifier (AGC-EDFA) with a variable optical attenuator (VOA) has been reported as switching system equipment [2]. A high-speed and low insertion loss (IL) VOA will be a key device for realizing such equipment.

Various types of VOA have been proposed including electro-optic (E-O) effect, electro-absorption (E-A) effect, magneto-optic effect, and micro electro mechanical system (MEMS) devices. In particular, a VOA incorporating the E-A effect or E-O effect can operate at high speeds of 1 μs or less. The former presents the problem of a large power consumption. The latter has two types: the waveguide type and the bulk type. The waveguide type with an epitaxial Lead-Lanthanum-Zirconate-Titanate (PLZT) can be controlled with a low voltage but the IL and polarization dependent loss (PDL) are typically very large [3]. The bulk type can achieve a lower IL and PDL. However, a high voltage of around 200 V is needed to operate a typical VOA. To achieve a high voltage and a high speed of around 1 μs for a drive circuit is very difficult. Reducing the drive voltage for the bulk type is a critical issue and then it can make directly to realize high speed performance including a drive circuit. Therefore, to maintain high speed and low loss simultaneously is a challenging issue.

This paper proposes a novel E-O type VOA with a trapezoid bar structure made of PLZT ceramics. The VOA overcomes the difficulty of supporting a fast response and low loss simultaneously, and has realized a high speed of 400 ns with a 27-V driving voltage and a low 1.5-dB IL.

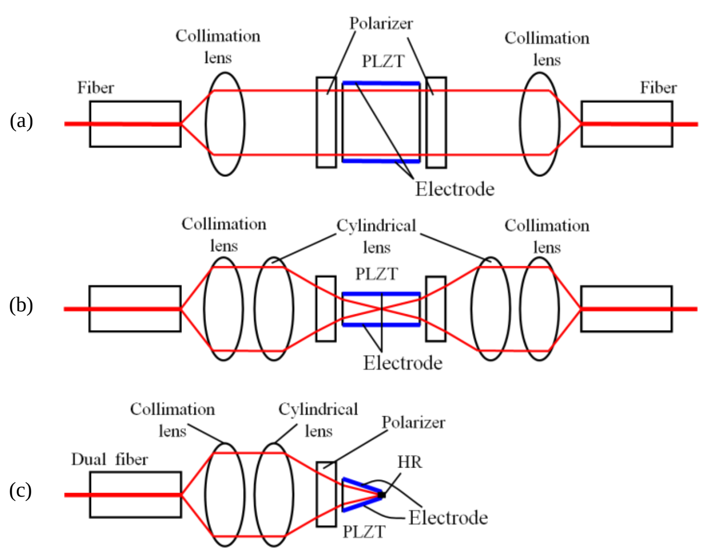

Fig.1 Optical structure of conventional and new VOA

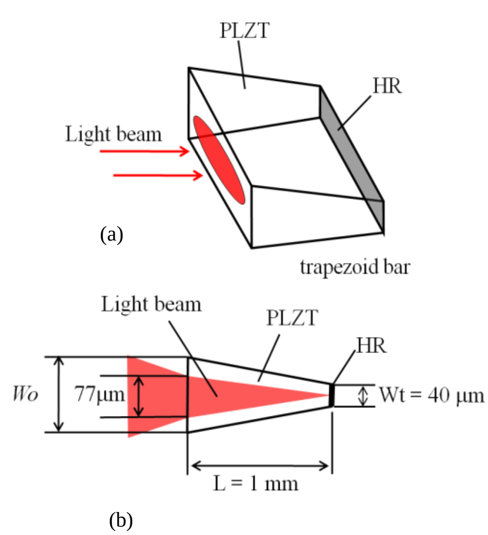

Fig. 2 Trapezoid bar structure and dimensions

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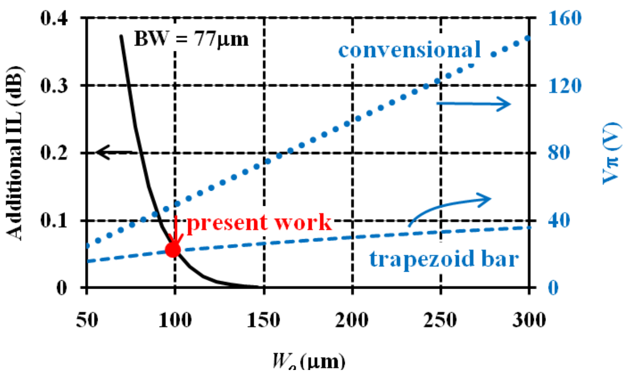

Fig. 3 W_o dependences of additional IL and V_π

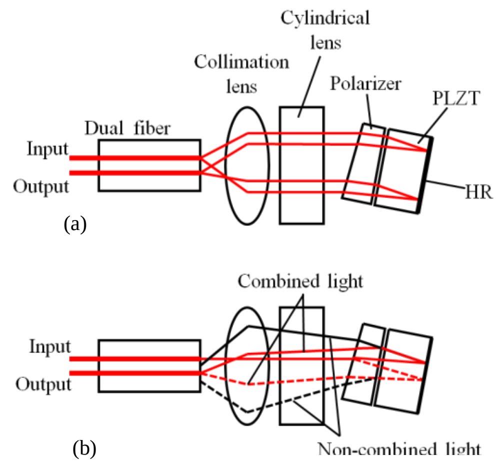

Fig. 4 Light ray path in VOA

2. Design of trapezoid bar structure

Figure 1(a) shows the optical structure of a conventional VOA. PZLT ceramics as an E-O material is placed between two polarizers [4]. The diameter of the open window for the PLZT should be larger than that of the parallel beam from a collimation lens. PLZT electrodes would thus have a wide gap, then the driving voltage would become very high.

A focusing lens system equipped with cylindrical lenses is effective for narrowing the gap as shown in Fig. 1(b). To reduce the gap to almost the physical limit, a trapezoid bar shape PLZT is adopted as shown in Fig. 1 (c). This can greatly reduce the driving voltage. In addition, a small size and small number of components can be achieved by employing highly reflective (HR) film. The reflection type VOA module, which has input and output fibers on one side, also has considerable flexibility when it is placed on a circuit board.

Figure 2 (a) shows the shape of the trapezoid bar we adopted and (b) shows the dimensions of the light beam focused on the HR film.

V_π can be expressed as follows.

$$V_\pi = W_o\sqrt{\frac{\lambda}{Ln^3R}} \qquad (1)$$

W_o, L, n, R, and λ are width of the open window, length, refractive index, electro-optic co-efficiency of PLZT, and wave length, respectively. In Fig. 3, the dotted blue lines show the calculated V_π in case of L = 1 mm and λ = 1550 nm for conventional and trapezoid shape PLZT, respectively. If W_o is 300 μm, for example, V_π will be 150 V for the conventional shape PLZT. For the trapezoid bar PLZT, V_π can also be calculated with equation (1) by replacing W_o with W_{eff} as defined as follow, $\left(\frac{1}{W_{eff}}\right)^2 = \text{average}\left(\frac{1}{\text{Erectrode gap}}\right)^2$. The narrower W_o is, the lower V_π will be, and then the V_π value of the trapezoid bar will fall below that of the conventional type.

The propagation loss through the trapezoid bar can be estimated with Gaussian beam coupling theory using the following equations.

$$IL = 10\log_{10}\int_{-Gap/2}^{Gap/2}|\varphi(x)|^2 dx \qquad (3), \qquad \varphi(x) = \left(\sqrt{\frac{2}{\pi}\frac{1}{BW}}\right)^{\frac{1}{2}} \exp\left(-\frac{x^2}{BW^2}\right) \qquad (4)$$

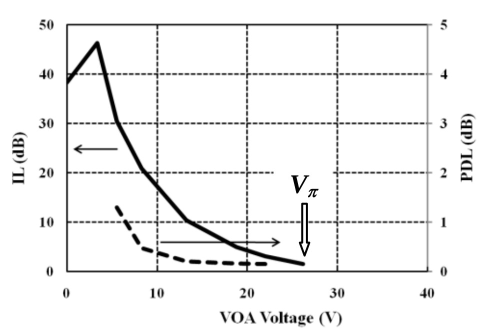

Fig. 5 IL and PDL of VOA

The propagation loss means additional IL. The additional IL shown by the solid line increases rapidly with decreasing W_o at around 100 μm.

To realize a much lower V_π and additional IL simultaneously, W_o is designed to be 100 μm and then the V_π and additional IL can be estimated as 22 V and 0.05 dB, respectively.

The propagation beam profile in the cross-section direction in Fig. 1(c) is shown in Fig. 4(a). The input light beam is reflected by the HR film of the PLZT and is focused on the output fiber again. Figure 4(b) shows the center ray of the propagation beam. The input beam is divided into ordinary and extraordinary rays by the polarizer. The rays reflected at the HR film are converted to combined rays or non-combined rays. When a drive voltage of V_π is applied to the PLZT, all the rays divided into two components in the middle are perfectly focused at the output fiber and then theoretically the attenuation will be infinitely small. Meanwhile, when no drive voltage is applied, the rays no longer focus at the output fiber. Thus a variable optical attenuation function can be obtained by varying the drive voltage.

The configuration concept with the polarizer is very similar to that of typical isolators, and in theory the VOA has no PDL with a V_π applied voltage .

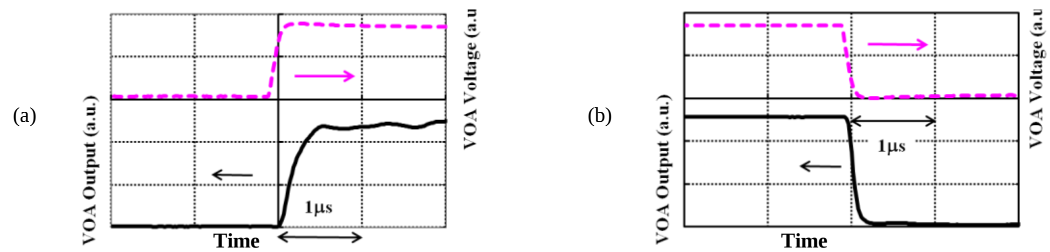

Fig. 6 Transient response o characteristics f VOA

3. Experimental result and discussion

Figure 5 shows the IL and PDL as a function of the VOA drive voltage. The measured V_π at minimum IL is only 27 V, which is a quarter of the typical value or less. This value is slightly larger than the calculated value of 22 V. The 4-V offset is caused by residual stress distortion induced in the trapezoid bar during the fabrication process. This offset is the reason for the difference. This low drive voltage makes the VOA response speed faster including the drive circuit performance.

The minimum loss is only 1.5 dB including the additional IL. The value consists of a 0.6-dB coupling loss, a 0.3-dB absorption loss, a 0.5-dB additional loss induced during assembly, and a 0.1-dB additional IL. The PDL is suppressed to less than 0.5 dB where the IL is less than 20 dB.

The transient responses are measured while applying a drive voltage consisting of a 10 kHz rectangular wave. Figure 6(a) and (b) show the measured rising and falling transient response, respectively. The broken lines are the control drive voltages and the solid lines are the VOA response. Rising and falling times of the drive voltage, which are defined as the time between 10% and 90% of the step height, are 100 ns. The rising transient time, T_r and the falling transient time, T_f of VOA are 400 ns and 100 ns, respectively. The difference between T_r and T_f is fundamentally caused by the nonlinear relationship between the IL and the drive voltage. T_r is larger than T_f because of the very small derivative for the drive voltage at minimum loss.

The VOA size from the fiber edge to the HR film at PLZT is only 13 mm, which is shorter than the typical value.

4. Conclusion

A novel reflection type VOA with a trapezoid bar PLZT was proposed. The drive voltage can be reduced by minimizing the electrode gap. This VOA has realized a small V_π that is a quarter of the conventional value or less. This low drive voltage increases the VOA response speed including the drive circuit performance. In general, it is difficult to support a fast response and a low loss simultaneously. The VOA has overcome this difficulty owing to the novel trapezoidal PLZT, and has achieved a 400-ns response and a 1.5-dB loss simultaneously. In addition, a small size and small number of components can be achieved by using HR film. The reflection type VOA module with its input and output fibers on one side also has considerable flexibility for assembly on a circuit board.

5. References

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