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LiNbO3 Optical Intensity Modulator Packaged with Monitor Photodiode

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***Abstract*–The assembly technique to simply install a monitor photodiode (PD) with a $LiNbO_3$ (LN) Mach-Zehnder modulator in the same package is proposed. A light radiated from the Mach-Zehnder Y-branch toward the LN output facet is lead into a glass bead, which is bonded to the LN facet as a fixture of the optical fiber. The end of the glass bead is cut to have an angled face, and the radiated light is reflected normal to the LN waveguide axis and toward the PD fixed on the side of package. The curved surface of the glass bead is effective to roughly focus the light onto the PD. We demonstrate that such monitor PD outputs an intensity modulation exactly reverse to the LN output modulation with a sensitivity higher than 0.03 A/W per optical output power of LN, indicating a usability of the PD output to monitor the drift of LN modulator.**

***Index Terms*–Drift, lithium niobate, modulator, photodiode.**

I. INTRODUCTION

WITH A HUGELY increasing demand for optical commu nication capacity, installation of high-speed dense wavelength-division-multiplexing (DWDM) systems over 10Gb/s is rapidly spreading to worldwide communication sites.The lithium niobate (LN) external optical intensity modulatorsare an indispensable device to such a high-speed transmission system, because of their broader bandwidth, suppressed chirping characteristics, independency to wavelength, etc. [1]. However, as the operating point of LN modulator output changes slightly depending on temperatures and drifts chronologically, in order to adjust and maintain the modulator output status [2], the signal from LN modulator is partially divided by fiber-coupler to input it to a monitor photodiode (PD) in the bias feedback control circuit [3]. Although the practical usage of LN modulators has been established with their high quality, the recent demand to compact systems strongly needs an integration of PD and LN chips in the same package. The purpose of our study is to realize such component modulators using simple assembly technology.

In this regard, there are two methods to obtain a monitor signal from the LN waveguide. The first method is to integrate a waveguide coupler after the Mach-Zehnder waveguide, and cut a part of the modulated signal as a monitor signal. The monitoring sensitivity can be adjusted by the design of the waveguide coupler, although the output power from the LN modulator is slightly lost depending on coupler performance. Another method uses a light radiated at the Y-branch of Mach-Zehnder without inducing any excess loss in main output signal. Kubota *et al.* reported previously on this monitoring method, in which they installed additional Ti-indiffused region (waveguide) near the Y-branch in order to lead the radiated light toward the PD chip placed facing to the LN chip facet (normalized sensitivity = 0.01 A/W) [4]. In this letter, we propose a novel and simple technique to lead out the radiation without any guided region on the LN chip.

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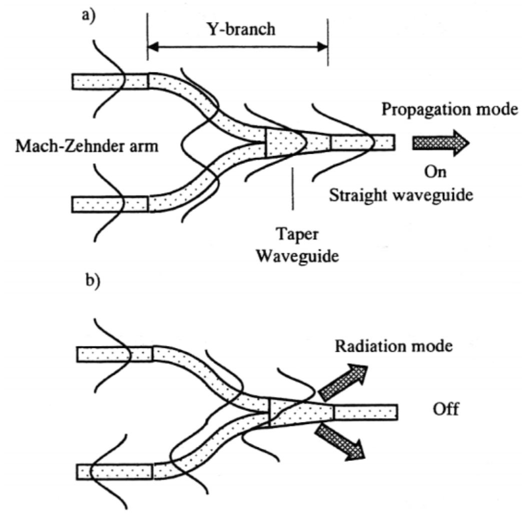

Fig. 1. Optical switching in the Mach-Zehnder waveguide modulator; (a) ON state and (b) OFF state.

II. DESIGN CONCEPT

Fig. 1 shows a schematic illustration of the output Y-branch waveguide portion after a pair of Mach-Zehnder waveguide arms; (a) for the ON state of Mach-Zehnder switch, and (b) for the OFF state. The ON state appears when a degree of the optical phase difference of Mach-Zehnder arms is $n\pi$ *(n = 0 or an even number), and the lowest order propagation-mode is induced at the Y-branch. The first propagation-mode is to be output from the LN modulator as the ON signal. When in the OFF state shown in Fig. 1 (b), the second order propagation-mode is generated at the Y-branch. The second propagation-mode is to be radiated at the position, where the waveguide is narrowed and the second propagation-mode results into cutoff condition (radiation-mode). The LN modulator output the OFF signal. Our proposed device design uses this radiation-mode as the monitor signal without any losses in the ON state signal of the modulator.

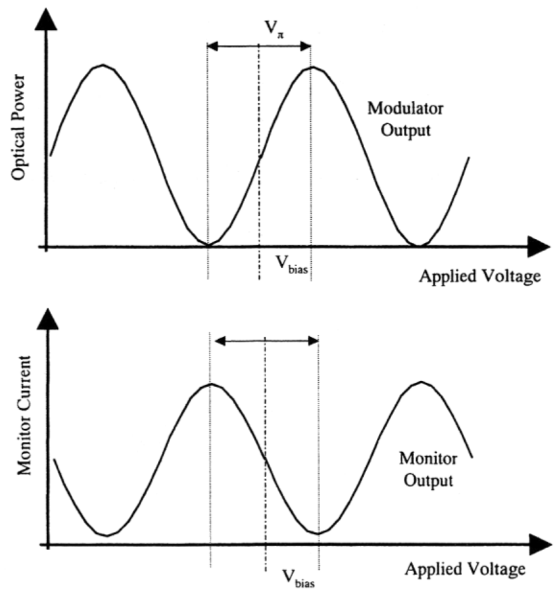

Fig. 2. Relationship between the LN modulator output (upper diagram) and the monitor output (lower diagram).

Fig. 2 exhibits the relationship between the modulator output signal and the monitor signal, in which the horizontal and the vertical axes denote the applied voltage and the optical power (monitor current), respectively. The polarity of the monitor signal modulation is expected to have a completely opposite sign of the modulator output modulation with the same half-wave voltage *VTT.* Thus, when the optical output power *P* from the modulator is expressed by

$$P = [1 + \cos(\phi + \phi_{\mathrm{bias}} + \varphi)]/2 \tag{1}$$

the output current *I* from monitor PD can be given by the equation

$$I = A[1 - \cos(\phi + \phi_{\mathrm{bias}} + \varphi)]/2 + \mathrm{I_N}. \tag{2}$$

The phase parameters in (1) and (2) are ϕ for a signal voltage, ϕ_{bias} for a dc bias voltage, and φ for a unforeseen asymmetry in Mach-Zehnder arms. In (2), a coefficient *A* denotes the efficiency of monitoring system and I_N denotes the noise current, mainly caused by uncoupled light between LN waveguide and optical fiber. The magnitude of I_N influences the extinction ratio of monitor output.

The proposed device design to monitor the radiation is schematically illustrated in Fig. 3. Optical fibers for carrying the optical signal are butt-coupled to input and output ends of the LN waveguide by epoxy adhesive material together with glass beads for reinforcement of their bonding strength. On the other hand, the monitor light radiated from the Mach-Zehnder Y-branch propagates through the LN bulk and reaches to the LN facet. Thus, a part of the radiated light is input into the body of the glass bead bonded to the LN output terminal. As shown in Fig. 3, the end of the output glass bead is cut to make a certain angle (about 45°) to the axis, at which the monitor light is reflected to a direction normal to the LN chip. Through the curved surface of the glass bead, the reflected light is to be focused on the PD placed near the LN chip. Key parameters in our design to obtain higher monitoring performance are shown in the next section.

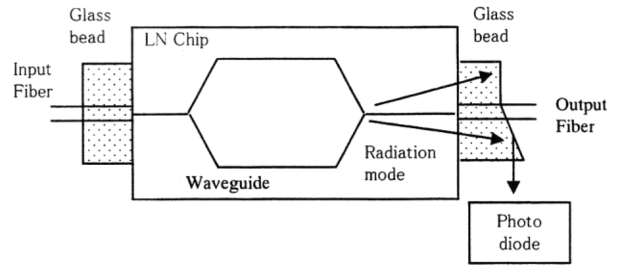

Fig. 3. Schematic illustration of the monitoring system ofLN radiation-mode byPD.

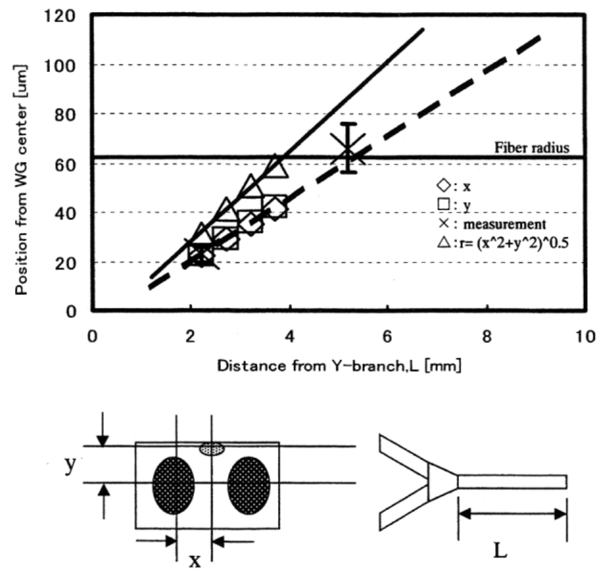

Fig. 4. Positional changes of the radiated light center appearing on an LN chip facet as a function of a length *L* of straight waveguide after the Mach-Zehnder Y-branch. Two plots marked by a cross with error-bar denoting measurement results and the others denoting calculation results.

III. DESIGN PARAMETERS

The position of monitor light at the LN facet depends on the length of the straight waveguide extruding from the Y-branch, and can be estimated using beam propagation method (BPM) [5]. Fig. 4 shows the calculation results, in which the horizontal axis denotes a length *L* from the Mach-Zehnder Y-branch, and the vertical axis denotes the position of the radiation light center measured from the waveguide. The position is shown by *x* and *y* coordinates (marked by diamonds and squares), and also by distance *r* (triangles). As is seen, with increasing the waveguide length *L,* the position of the radiation light center increases proportionally. In Fig. 4, measurement results on *z*-cut/*x*-propagation LN Mach-Zehnder Ti-indiffused waveguides are plotted by crosses and error bars, being consistent with the calculation results. In the following demonstration, the condition of *L* = 5

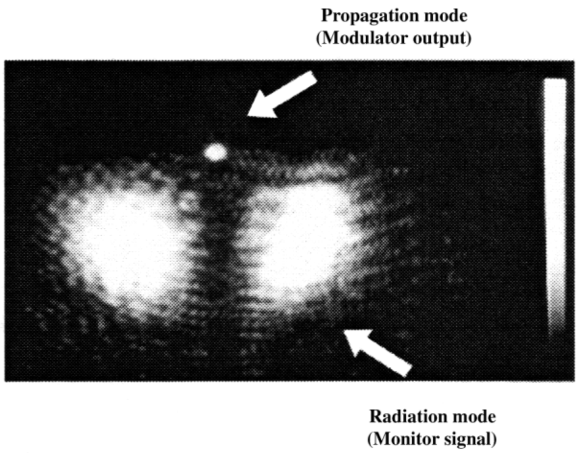

Fig. 5. Near-field image ofLN modulator output-end.

TABLE I
PERFORMANCE OF MONITOR PD INSTALLED IN SEVERAL LN MODULATORS

Sample	Monitor PD Sensitivity Normalized by LN Optical Output [A/W]	Monitor Tracking Stability between 5 and 65°C [dB]
L10-013-27	0.152	0.6
L10-013-28	0.164	0.6
L40-002-06	0.036	0.9
L40-002-08	0.203	1.0
PA-003-06	0.473	0.1
PA-003-08	0.147	0.2
PA-003-11	0.259	0.1
average	0.205	0.50
σ_{n-1}	0.136	0.38

mm, providing $r = 80\ \mu$m larger than the inner-diameter of the glass bead, was chosen.

IV. EXPERIMENTAL RESULTS

In order to obtain higher monitoring current and extinction ratio, there is a necessity to know the planar distribution of the radiated light on the LN facet. Fig. 5 exhibits a typical near-field image of the LN facet, in which the confined small spot is the output Ti: $LiNbO_3$ waveguide and the pair of diffused regions below the waveguide correspond to the monitor light radiated from the Mach-Zehnder Y-branch. Because the glass bead has a 130-μm-diameter through-hole to hold the fiber, in order to efficiently receive the radiated light at the bead body, the monitor light is designed to appear more than 65 μm away from the waveguide. Generally, the outer diameter of the glass bead is 1 mm or larger. A conventional Mach-Zehnder modulator chip was cut and polished, until its straight waveguide length after the Y-branch became 5 mm. A pair of fibers were aligned to the waveguide and bonded with the normal glass bead for input-port and with the angled glass bead for output-port (see Fig. 3) using UV-curable epoxy. The position of PD was actively adjusted in order to achieve the highest gain and fixed in the package using an epoxy. These devices were assembled together in a hermetically sealed package. Performance of the PD monitor was evaluated using $\lambda = 1550$ nm light at room temperature.

As a demonstration, seven hermetically sealed LN modulators with the built-in PD were fabricated and their obtained monitor performances are listed in Table I. The typical optical power output from the LN modulator and from the monitor PD are shown in Fig. 6. As estimated in Fig. 3, the monitor signal was observed to form the completely reverse modulation pattern to the LN signal. A difference in the operating point (modulation quadrature) and the $V\pi$ between the LN modulator signal and the monitor signal was measured to be 0.03 V and 0.0 V, respectively. The sensitivity of the monitor output was measured to be 0.036 ~ 0.473 A/W per the output optical power from the LN modulator (see Table I). In Table I, the monitor sensitivity is determined by $(I_{max} - I_{min})/P$, where I_{max} and I_{min} correspond to PD output currents at modulation peak and bottom, respectively, and P is the maximum optical output power from LN modulator. Further, a tracking performance of the monitor PD over ordinary device operation temperatures was found to be stable (≤1 dB), as shown in Table I. In our opinion, the obtained performance of the proposed monitoring system is suitable to be applied to practical modulators.

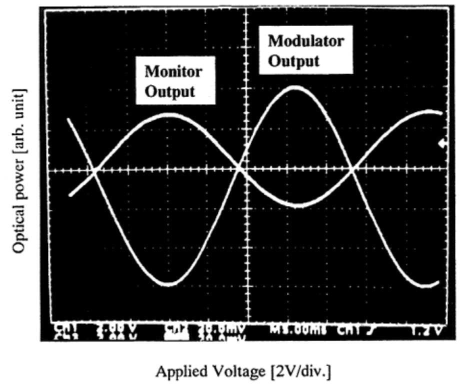

Fig. 6. Relationship between the LN modulator output and the monitor output, demonstrated for z-cut LN modulator samples.

V. CONCLUSION

We proposed a simple and practical assembly design to install the built-in monitor PD in the LN Mach-Zehnder optical modulator package. Only the PD chip and the angled-cut glass bead to reflect the radiation-mode are newly installed devices, and mechanical structure and reliability are almost the same as those of conventional modulators without PD. The monitor signal modulation drifts together with the LN output modulation, and the monitoring sensitivity was demonstrated to be high enough for practical application.

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