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Ti: $LiNbO_3$ Acousto-Optic Tunable Filter (AOTF)

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We have developed the following new elements for an AOTF: an intersecting waveguide PBS which has a high extinction ratio, low loss, and wavelength independent characteristics; a film-loaded SAW guide (SAWG) which has a strong confinement, excellent filter characteristics, and provides a high design flexibility; and a 0-gap directional coupler type reflector which enables high-performance waveguide integration.
These elements were combined to construct an AOTF consisting of five film-loaded SAWGs. The through and drop lights in this AOTF are filtered by three stages of the new SAWG. The 3 dB bandwidth and extinction ratio are 0.37 nm and less than –27 dB, respectively.
An optical ADM system that incorporated the new AOTF has demonstrated 10 Gb/s ⋇ 32-channel transmission with a 0.8 nm wavelength spacing.

1. Introduction

Recently, optical transmission systems that use a loop or mesh configuration as well as a conventional point-to-point configuration have been constructed, and WDM techniques are being used to satisfy the exploding demand for transmission capacity.

Much effort is being made to find methods of manipulating multiple wavelengths to achieve high-performance WDM systems. The OADM, which adds and drops optical signals on a transmission line, performs the most basic function of WDM networks and can be constructed in many ways. For example, an arrayed waveguide grating filter can be used to separate each wavelength, the drop wavelengths can be selected using matrix switches, and the through light can be constructed using an AWG filter. The simplest solution is to use a tunable filter which separates the optical signal into the drop light and the through light.

A $LiNbO_3$ waveguide-type acousto-optic tunable filter (AOTF) has many excellent characteristics, for example, simultaneous multi-wavelength selection, a broad tunable bandwidth of more than 100 nm, and direct wavelength selection without scanning. The AOTF has been studied in many organizations since 1969. However, many problems remain that prevent its use in practical systems.

We started AOTF development in 1996 and have developed several new techniques which improve AOTF performance in an OADM.[1),2)]

2. Problems affecting conventional AOTFs

AOTFs are required to have polarization independent characteristics. To meet this requirement, a polarization-diversity configuration using a wavelength independent polarization beam splitter (PBS) is required.

Today's WDM systems use a 0.8 nm wavelength spacing, which requires filters with an FWHM of less than 0.4 nm. However, the FWHM of a conventional AOTF is more than 1 nm because of wafer size limitations. Therefore, a technique for decreasing the filter bandwidth is also required.

In an OADM, the cross-talk between the drop light and the through port must be decreased to the extremely low level of less than –40 dB because the drop light and add light can generate coherent beat noise.

We have to solve another beat noise problem in the AOTF, which is caused by the interference between light excited by the Doppler shift of the SAW. This beat noise increases with the number of wavelengths and is inversely proportional to the wavelength spacing and the extinction ratio of the AOTF. Therefore, in multi-channel and dense wavelength division multiplexing (DWDM) systems, a high extinction ratio is required in the AOTF.

3. New elements developed for AOTFs

3.1 Intersecting-waveguide polarization beam splitter (PBS)

The proton exchange type PBS shown in **Figure 1(a)** is the most popular PBS used in AOTFs.[3] It has several excellent characteristics; namely, a high extinction ratio and a small wavelength dependency. However, it also has a large excess loss caused by mode field mismatch between the Ti indiffused waveguide and the proton-exchange waveguide. It also has the demerit of being a long device (~10 mm).

We have therefore developed the intersecting-waveguide PBS shown in **Figure 1(b)**. In this figure, *Lc* and *Wc* are the length and center width in the intersecting region, respectively. The processes for fabricating this PBS can be performed simultaneously with other processes for waveguide fabrication. This intersecting waveguide functions as a directional coupler whose operation depends on the beat between the odd-mode light and even-mode light for TE-mode light and TM-mode light, respectively. It propagates the TE-mode light to the cross output port and the TM-mode light to the parallel output port. This polarization selectivity is due to the birefringence of $LiNbO_3$. **Figure 2** shows the relation between the extinction ratios and the intersection length, *Lc*, of the PBS for TE-mode and TM-mode light. The figure shows that the extinction ratios of both polarizations are less than –30 dB. Extinction ratios lower than –30 dB are only obtained over a

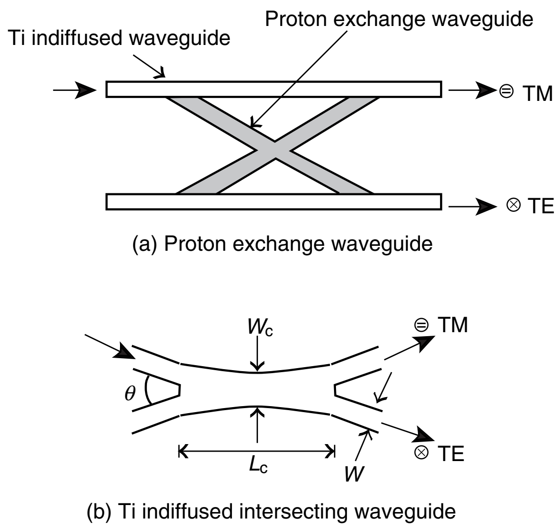

Figure 1
Waveguide PBS.

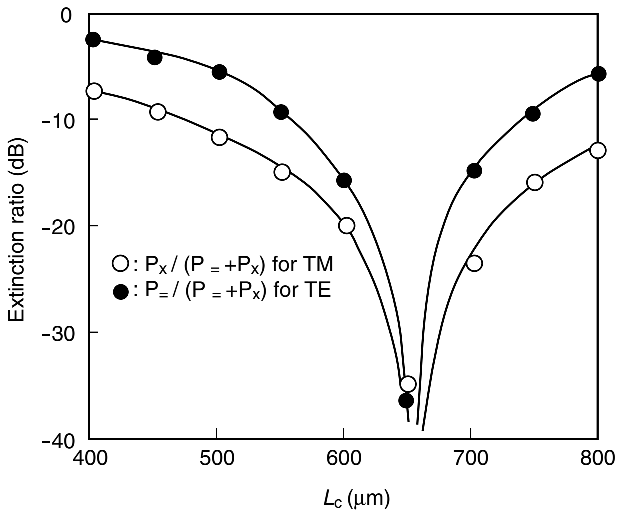

Figure 2
Characteristics of PBS.

very small range of *Lc*. This seems to be a critical condition, but the extinction ratios of this PBS are stable over a wide bandwidth. This wide bandwidth is due to the device's short interaction length of 0.6 μm. This PBS also has the merit of a low excess loss. The excess loss is minimized by the shape of the intersecting waveguide and has a minimum value of 0.15 dB.

3.2 Film-loaded SAW guide (SAWG)

The performance of an AOTF greatly depends on the design of its SAW guide (SAWG). A Ti-deep-diffused SAWG (**Figure 3(a)**) is the most popular,[4] but it is quite wide because of the need for sufficient distance between the Ti SAWG and the Ti optical waveguide. This makes it difficult to integrate multiple AOTFs in a single chip and also decreases the design tolerances.

This paper proposes a new SAWG design, called the Film-loaded SAWG, which uses a film as shown in **Figure 3 (b)**. The confinement in this new type of SAWG has an exact relation with the device's width, thickness, and film material, but does not have a distinct relation with the SAW propagation speed on the film. The guiding mechanism in this new SAWG is not fully understood, but it is suspected to depend on the combination of the loaded effect, stiffness effect, and electric-charge shortening effect.

Transparent materials of SiO_2 or In_2O_3-doped SiO_2 are selected for the SAWG film. In the case of a pure SiO_2 film, the confinement of the SAW is almost the same as in the Ti-deep diffused SAWG. The confinement can be set within a wide range by changing the In_2O_3 compound. The strongest confinement is obtained with a SiO_2 film containing 60 wt% In_2O_3, which gives a confinement that is 10 times larger than that of pure SiO_2 films. This result indicates that the film-loaded SAWG has an advantage when it comes to integrating multiple AOTFs in a single chip.

This SAWG can be designed independently with an optical waveguide, so apodization is flexible. For apodization, we used a straight SAWG which intersects with the optical waveguide as shown in **Figure 4**. This method is very simple and can provide good side lobe suppression. **Figure 5** shows the transmission characteristic of this SAWG. The side lobe suppression is -24 dB, and the 3 dB bandwidth is 1.4 nm.

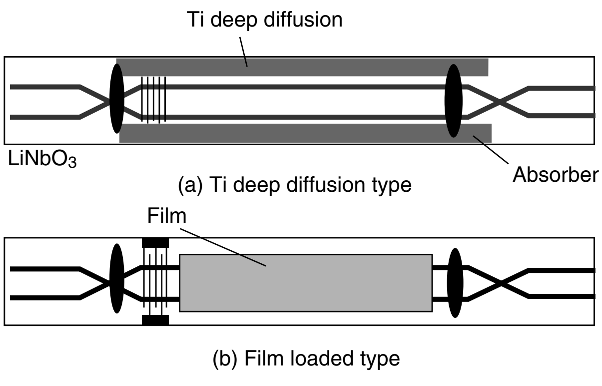

Figure 3
SAWG.

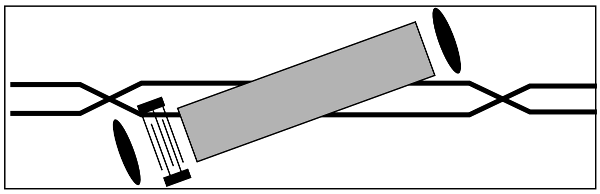

Figure 4
Apodized SAWG.

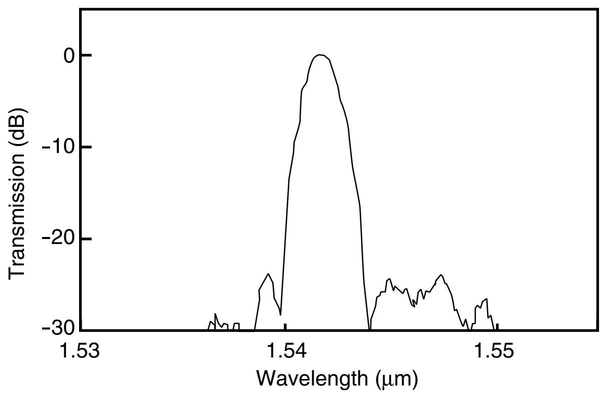

Figure 5
Transmission characteristic of intersecting SAWG.

3.3 Waveguide reflector

The bandwidth of an AOTF is proportional to the chip's interaction length. However, because the chip length is limited by the wafer size, we folded the long-waveguide circuits so they can fit within a chip.

To fold the waveguide, we developed a new type of waveguide reflector. The conventional waveguide reflector is shown in **Figure 6**. It reflects the light geometrically over the large reflecting angle θ, which is usually more than 4°. However, from today's manufacturing point of view, the excess loss of this reflector is too high.

To solve this problem, we developed the waveguide reflector shown in **Figure 7**, which uses a 0-gap directional coupler waveguide. First, we designed a 0-gap directional coupler which directs both the TE-mode and TM-mode light to the cross output port. The waveguide is cut at the center of the intersecting region, and a metal mirror is set at the cut end-face. In this design, the intersecting-region is three times longer compared with the case in a PBS because the beat period of the TM mode is three times longer than that of the TE-mode.

This reflector has more than 10 times the manufacturing tolerance of the conventional design.

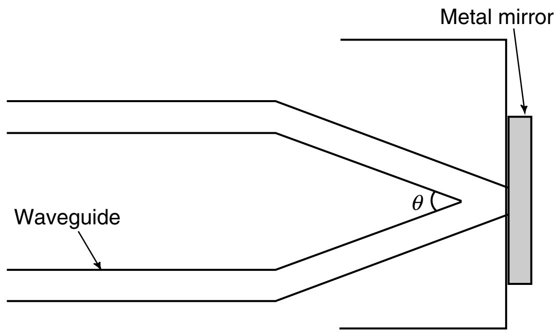

Figure 6
Conventional waveguide reflector.

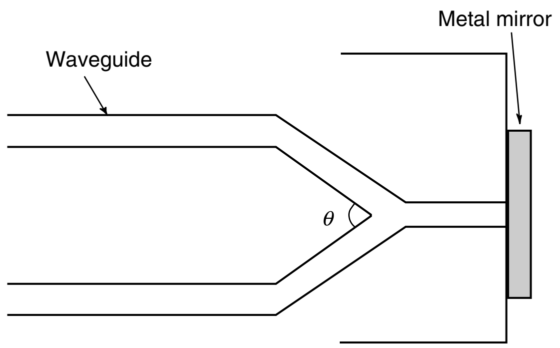

Figure 7
0-gap directional coupler type reflector.

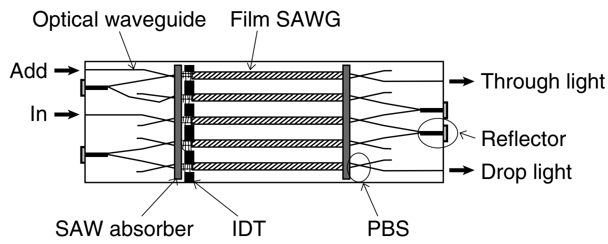

Figure 8
Integrated AOTF.

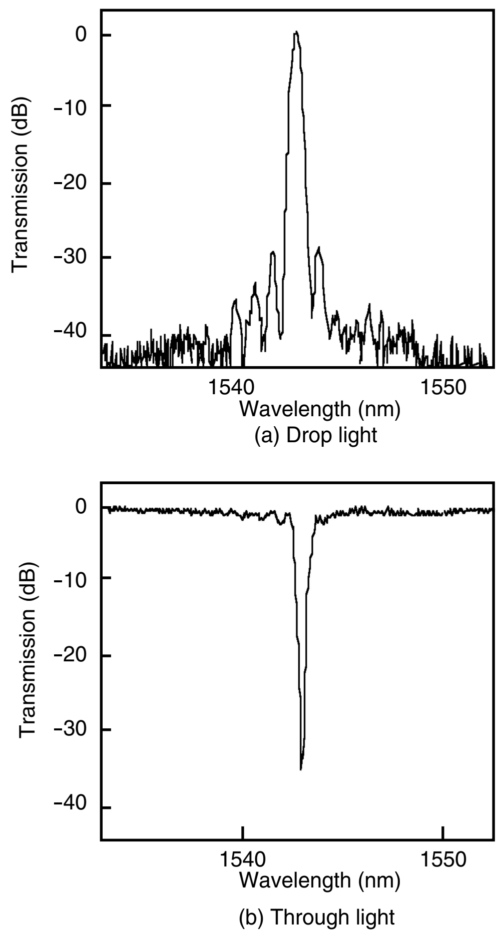

Figure 9
Filter characteristics.

4. Integrated AOTF

Using these new techniques, we fabricated the integrated AOTF shown in **Figure 8**. The device is a single chip containing five AOTFs and four reflectors that interconnect them. The input light is divided into the through light and drop light by the first-stage AOTF (center AOTF), which consists of a PBS, the new film-loaded SAWG, and an inter-digital transducer (IDT). First, the input light propagates through the middle SAWG and then back in the opposite direction through the two adjacent SAWGs after being reflected by the newly designed reflectors. The light is again reflected by two more of the new reflectors, propagates through the top and bottom SAWGs, and emerges as the through light and the drop light from the top and bottom, respectively. The through light and drop light therefore is filtered once by the same SAWG and then twice more by two different SAWGs.

Figure 9 shows the measured wavelength spectrums of the through light and drop light. The 3 dB bandwidth of the drop light is 0.37 nm. The side lobe suppression is –27 dB. The extinction ratio of the through light is –37 dB.

5. Demonstration of OADM

An OADM incorporating the AOTF described above was demonstrated at Supercomm'98 held in Atlanta, USA last year. The OADM comfortably performed 10 Gb/s × 32-channel transmission with a 0.8 nm spacing.

6. Conclusion

We have developed the following new elements for an AOTF: an intersecting waveguide polarization beam splitter, a film-loaded SAWG, and a 0-gap directional coupler type reflector. These new elements make it possible to integrate an AOTF in a single chip. An integrated AOTF built using these new elements achieved a 3 dB bandwidth of 0.37 nm and an extinction ratio of –37 dB. The new AOTF was used to demonstrate 10 Gb/s × 32-channel transmission with a 0.8 nm spacing at Supercomm'98 held in Atlanta, USA in 1998.

References

1) M. Seino et al.: Tunable add/drop filters using $LiNbO_3$. LEOS'97, Summer Topical Meeting, PD, Aug. 1997.
2) T. Nakazawa et al.: Ti: $LiNbO_3$ AOTF for 0.8 nm Channel - Spaced WDM. OFC'98, PD-1, 1998.
3) A. d'Alessandro et al.: Polarisation-independent low-power integrated acousto-optic tunable filter/switch using APE/Ti polarisation splitters on lithium niobate. *Electronics Letters*, **29**, pp.1767-1769(Sept. 1993).
4) Le Nguyen Binh et al.: A Wide-Band Acousto-optic TE-TM Mode Converter Using a Doubly Confined Structure. *IEEE J. Quantum Electron*. **QE-16**, pp.964-971(Sept. 1980).

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