40 years anniversary of Ti:$LiNbO_3$ and beyond

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Abstract: This tutorial lecture covers a historical and evolutional developments of Ti:$LiNbO_3$ integrated optics with current status and related future prospects.

Introduction: Ti in-diffused waveguide on $LiNbO_3$ waveguide is one of the most historical player in integrated optics as limited high speed electro-optic device suits to single mode fibers. Ti:$LiNbO_3$ waveguide was first reported in 1974 by I. P. Kaminow et al with Bell Labs.[1] Unfortunately he was lost the last year, however, the devices and basic technologies still survive with several advantages.[2]

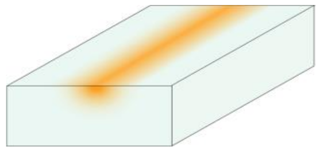

Fig.1 Schimatics of Ti:$LiNbO_3$

History of $LiNbO_3$: Ferroelectric lithium niobate has a pseudo illuminate structure with a trigonal crystal system. 20 years after of its first report in 1928 as a new material, it was successfully grown as a single crystal by flux method in 1949.[3] Then, $LiNbO_3$ and $LiTaO_3$ single crystal of so-called congruent composition without Li/Nb stoichiometric ratio small bowls were first grown by Cz-method in 1965.[4] Both single crystals have been supplied to surface devices mainly for consumer electronics such as oscillators, surface acoustic filters (SAW) and pyro-electric elements until even now evolutionary up to 6" diameter size. On the other hand, at first, their large Pockels coefficients ($r_{33} \cong 30$ pm/V) and nonlinear optic coefficients were interested for optoelectronic applications with high quality bulk single crystal. However, optical damage and drift problems with high half-wave voltage $V\pi$ up to KV prevented their applications in the real optical fields.

Ti:$LiNbO_3$ as an early integrated optics [5-14]: Since 1974, when we got easy fabrication method to make low-loss single mode waveguides by in-diffusion of Ti on $LiNbO_3$ (not on $LiTaO_3$ with low Tc) wafer around 1000 °C under Curie temperature of Tc ≅ 1130 °C, many reports had done for realization of "integrated optics" not only passive but also functional such as high-speed switch, phase/intensity modulator, TE/TM mode splitter and so on. In the early stage of research period, many types of waveguide structures were introduced; straight line (with curvature), directional coupler (D.C. with perfect coupling length, 3 dB coupling and others), Y-branch, Mach-Zehnder interferometer (MZI) with two Y-branches and arms, balanced bride (B.B.), X or asymmetric-X intersecting. They have relatively large curve radius because of small index change $+\Delta n$ of low Ti-concentration. But, mode size of Ti:$LiNbO_3$ is very close to and single-mode fiber (including polarization maintaining fiber) and they easily couples each other with low loss. And $V\pi$ was dramatically reduced to several volts with appropriate interaction length of electrode and waveguide.

In 1980s, longer wavelength light sources were developed fitting to fiber low-loss wavelength region of (1.3 -) 1.55 μm. This wavelength region is comfortable for Ti:$LiNbO_3$ with high threshold of optical damage, and wider broadband SW/modulators were developed. However, drift problem remained and moreover, pyro-electric induced thermal drift was enlarged on thick dielectric buffer layer putted to compensate lightwave and microwave mismatch with different index caused by large dielectric constant of $LiNbO_3$. Fujitsu group including the author had solved successfuly this thermal drift problem introducing Si coated semi-conducting SiO_2 buffer layer on Z-cut Ti:$LiNbO_3$ in mid 1980s and established first commercially available 10Gbps MZI intensity modulators with automatic bias control for DC drift in 1990. They demonstrated stable operation of fabricated fiber pigtailed package of MZI with hard heat shock test during InterOpto exhibition in Makuhari, Japan for several days in July of the same year. NTT first installed 10 Gbps terrestrial fiber transmission line in early 1990s using this device. TPC-5 undersea cable network also using Ti:$LiNbO_3$ MZI and EDFAs with 5 Gbps was installed in 1996. After then, dense wavelength division multiplexing (DWDM) with AWG (Arrayed Waveguide Grating) and MZI modulators, were rapidly introduced in real fields toward Photonic IT bubble in 2000-2002 as two big players of integrated optics besides of DFB-LDs.

Recent progress of Ti:LibO$_3$ MZI modulator and applications [15-21] : In mid-2000s after the photonic gracious, digital coherent technologies opened with digital signal processor (DSP). Ti:LiNbO$_3$ MZI IQ modulators still have important role in them. So-called nested or dual parallel MZI makes not only intensity but also phase of lightwave modulation simultaneously up to multi-QAM. MZI modulators with polarization division multiplexing 100Gbps per λ has been installed in 2012. Compared with other materials of MZI or other principle modulators such as electro absorption (EA), low or less chirp Ti:LiNbO$_3$ modulators have advantages in long distance transmission. In the other applications out of digital coherent or conventional digital fiber communications, more extinction ratio of MZI is required. Radio over fiber (ROF) is one of the most typical examples. A nested MZI essentially has a potential to get two-tone frequencies with high extinction ratio and effective to even scientific application. However, it has a difficulty of each three MZs individual DC bias control. We recently developed reduced DC bias control at Y-branch of single MZ named active Y-branch to achieve equivalent high extinction ratio. Figure 2 shows a schematic evolution diagram of Ti:LiNbO$_3$ MZIs starting from a phase modulation by straight line waveguide (1).

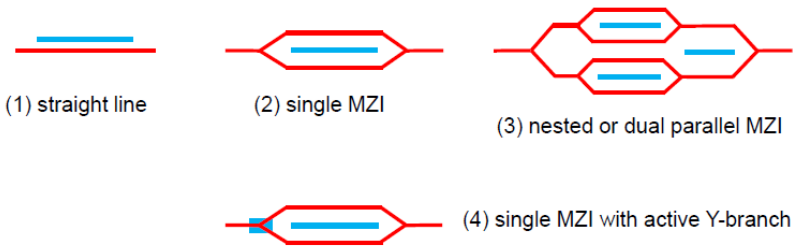

Fig.2 Evolution of Ti:LiNbO$_3$ MZI modulators

Other LiNbO$_3$ integrated optics for future possible applications [22-24] : Ti in-diffused waveguide, however, has many disadvantages such as small Δn or weak confinement of guided-wave field. Strong interaction and damage free characteristics are required for non-linear applications. Therefore other structures have been studied except Ti-diffused wavegude. MgO-doping in LiNbO$_3$ is very effective to reduce optical damage phenomena even in visible wavelength region and various waveguide fabrication technologies have been reported with dry etched rib structure on MgO:LiNbO$_3$.

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