Integrated devices
in ferroelectrics for optical modulations and sensing

D. Janner[1*], V. Pruneri[1,2]

[1] ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain
[2] ICREA-Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain
* email: davide.janner@icfo.es

Abstract: We will review the current status of domain inverted lithium niobate acousto- and electro-optic devices and show how the introduction of domain micro-engineering techniques can have a strong impact on modulators' performance enabling for a new class of integrated devices. We will also present potential applications of the proposed devices in increasingly important areas, such as advanced optical communication modulation formats, reconfigurable networks and sensors.

Keywords: Integrated devices, LiNbO3, domain inversion, acousto-optical modulators, electro-optical modulators, optical sensing

1. Introduction

Acousto-optic (AO) and electro-optic (EO) modulators are largely used in many different fields of science and engineering [1]. For instance in optical telecommunications, EO modulators are the key components in high speed optical data transmission (e.g. 10, 40 and 100 Gb/s). Other applications can be found in the fields of sensing and metrology ranging from electric field measurements in power plant based on EO modulators, to spectral slicing of super-continuum source in optical coherence tomography employing AO tunable filters. Given their EO and AO response, ferroelectrics are the material of choice to realize these devices. In particular, lithium niobate ($LiNbO_3$) has become the reference material for optical modulation in optical fiber telecommunications and is also widely used in the AO field. In $LiNbO_3$, the electro-optic and nonlinear optical properties are intrinsically related to the crystal orientation (also called poling orientation or domain) and single domain substrates are readily available commercially as wafers up to 5". By applying high electric fields (>20 kV/mm) through appropriate electrodes along the z-axis, domain inversion (DI) can be achieved and specific patterns of DI, either periodic or not, can be obtained. DI produces a sign reversal of the second-order nonlinear optical properties in particular the nonlinear optical coefficient and, the piezoelectric coefficient responsible for the EO and AO effects respectively. Recently, DI has been used to produce large bandwidth and low driving voltage modulation [2], a desired chirp value for the output EO-modulated optical wave [3], and to realize single-side-band modulators [4]. DI has also been employed in AO devices, leveraging its capabilities to generate bulk and surface acoustic waves [5,6] with uniform electrodes. In this contribution we will present the advances in EO and AO modulators based on DI and other advanced fabrication techniques along with their applications to devices for emerging modulator formats, spectral slicing in reconfigurable networks and light sources, and electric field sensing in harsh environments.

2. Acousto-optic and electro-optic integrated devices

In acoustics, DI in the form of periodically poled $LiNbO_3$ has allowed to induce electromechanical coupling exploiting new configurations [5,6], known as acoustic superlattices (ASLs) transducer. This new type of transducer significantly differs from standard interdigitated transducers (IDTs) or bulk wave resonators realized in a uniform piezoelectric medium since the acoustic waves can be launched using uniform coplanar electrodes, instead of periodic electrodes (IDTs). Therefore, the application of a uniform external electric field to the periodic structure will subject the domain walls to a periodic strain resulting from the periodic change in the piezoelectric coefficient, effectively acting as localized sound sources that produce acoustic wave generation (see fig. 1). Recently, it has been demonstrated that both surface (SAW) and bulk (BAW) acoustic waves can be generated using ASLs [6]. Both types of waves are of great interest in AO modulation and filters, although SAWs present more attractive features for integrated (optical waveguide) devices. In fact, SAW's acoustic energy is confined close to the surface of the substrate where optical waveguides can be fabricated. In contrast, BAW based AO devices usually need thicker substrates and the acoustic and optical powers are spread over a larger volume, thus requiring higher RF power drivers. An AO filter is proposed based on the combination of ASL generated SAW and by placing an optical waveguide in the middle of the coplanar electrodes. By carefully designing the electrodes or introducing a mass loading within the electrodes' gap optimized devices with 50 mW RF driving power are obtained [7]. The main application of such modulators is in AO tunable filters (AOTFs) for the fields of telecommunications and spectral filtering for laser sources. In telecommunications, SAW based multichannel reconfigurable optical add drop multiplexers (ROADM) based on this technology can help reducing the overall power consumption, the optical insertion loss and complexity of such devices avoiding the acoustic guiding film usually needed for IDT-based devices. One of the main applications in laser source is related to spectral slicing of supercontinuum sources for optical coherence tomography (OCT) replacing bulk acousto-optic filters with integrated devices allowing a reduced power consumption and setting the bases for an integrated technology highly compatible with fiber optic laser sources available nowadays.

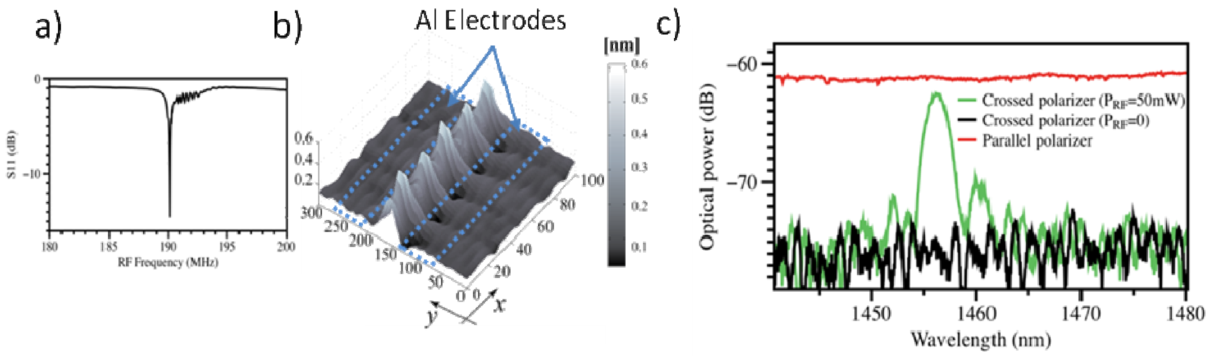

Figure 1. Typical response for an AO based superlattice SAW device based on DI with coplanar electrodes: a) RF S11 response, b) profile displacement of SAW measured by interferometric technique and c) low-power AO modulator performance.

$LiNbO_3$ optical intensity modulators are key components in current long-haul WDM high-bit-rate optical communications systems. Nevertheless, novel optical modulators using alternative modulation formats and new architectures are being actively studied in order to match the speed requirements of next generation systems for which higher capacity over long distance links and core networks will be necessary, primarily due to video applications. Moreover, those systems will require cost efficiency and adaptability to new environments, such as access networks. Though $LiNbO_3$ technology is considered quite "mature", it has already supported the introduction of many important breakthroughs in terms of network capacity and spectral efficiency. These types of device were first introduced for 2.5 Gbps systems, then scaled to 10 Gbps WDM systems and finally supporting 40G return to zero differential phase-shift keying (RZ-DPSK) and differential quadrature phase-shift keying (DQPSK) transmissions in a wide range of new commercial systems. The high extinction, broad-bandwidth and low driving voltage of $LiNbO_3$ devices also achieved with the help of DI, allow generation of clean and undistorted signal constellations in QPSK, 16-quadrature amplitude modulation (16QAM) and more complex configurations such as multicarrier and orthogonal frequency-division multiplexing (OFDM). The basic and most widespread configuration of an EO modulator consists of a Mach-Zehnder interferometer (MZI) structure and its applications range from simple on-off keying modulation to the new and more complex modulation formats. Improving the performance of the single MZI modulator either in terms of bandwidth or driving voltage is a mandatory step in the development of enabling technologies for next generation networks. DI can be employed to increase the figure of merit that links the bandwidth (BW) and driving voltage (V_π) with the added flexibility of fine tuning of the EO response of the modulator. A careful use of DI [8] allows for e.g. arbitrary EO response and of ultra-low-voltage MZI modulators as illustrated in fig. 2 where we show the performance of A DI modulator at 10 Gb/s operation with V_π<3V. Besides low power and cost effectiveness, another key point of optical integration is size reduction. Hybrid integration of $LiNbO_3$ modulators with silica-based PLCs is an enabling technology which reduces the chip size on $LiNbO_3$ substrate, allowing a more efficient utilization of the wafers in production and concentrating the technological effort on some building blocks for high-efficiency, high-speed electro-optic modulation, while leaving the optical splitting and combining functions to a different platform (PLC or similar). This approach is probably a good compromise also for the higher-level modulation schemes (e.g., 16- and 64-QAM).

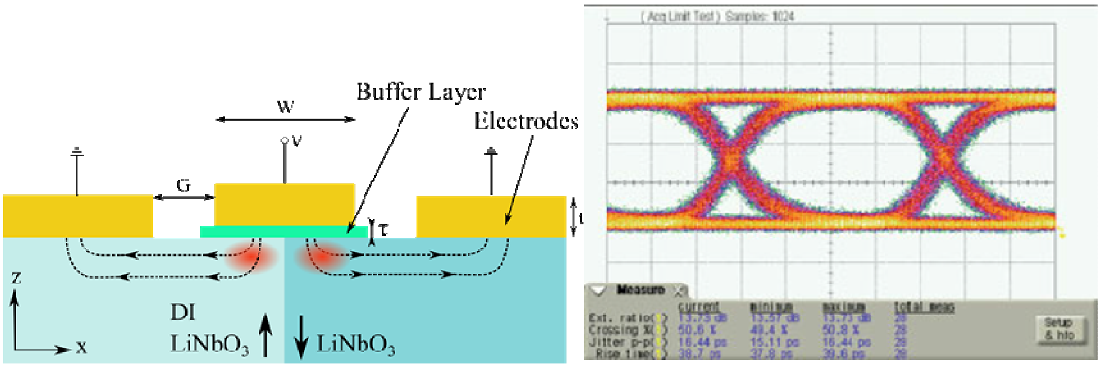

Figure 2. Cross section of an ultra-low voltage modulator (left) and typical eye diagram at 10 Gb/s (right)

3. Integrated ferroelectric based sensors

Common electric field meters typically use conductive parts, which can interfere with the field to be measured, and are very sensitive to electromagnetic noise. Moreover, frequency bandwidth limitations and 50Ω-characteristic impedance in the case of RF waveguide-based sensors limit the scope of applicability of such technology. Electro-optic (EO) devices present several intrinsic advantages compared to their electronic counterparts such as noise immunity, feasibility of electrode-free operation and consequently the possibility of operating even in harsh or dangerous environments. So far, several configurations of EO sensors have been reported, mostly based on waveguide interferometers or bulk polarization/phase rotation in a piezoelectric crystal [9]. The latter approach requires phase noise reduction/control techniques that are typically expensive to implement and may raise long-term stability issues. On the contrary, waveguide-based sensors directly convert the electric field value into an optical power variation, thus simplifying the interrogation system and potentially lowering the cost. In this context, MZIs are usually employed for their high sensitivity that can be as low as few hundreds of mV/m. Despite their very high sensitivity the nonlinear MZI response limits their dynamic range and their use in some installations, like electric plants or railway electric networks. In these systems, very bulky sensors need to be employed. Recently, we proposed an all-optical electric field sensor based on a proton-exchange waveguide near cut-off fabricated in z-cut $LiNbO_3$ and centered on a few microns wide domain-inverted region [8,10]. In the presence of an external electric field parallel to the z-axis of the device, the refractive index in the central inverted domain decreases (increases) while it increases (decreases) in the external domains. Thus, the optical mode is deformed so that, after a sufficient propagation length, a loss is produced due to a mode-profile mismatch of the guided modes between active and passive regions. Such a device is able to measure electric field strengths as high as 2.6 MV/m at low frequency and electric RF fields at 1.1 GHz with intensities ranging from 19 V/m to 23 kV/m, with a linear dynamic range greater than 60 dB. Furthermore, thanks to the insensitivity of the sensor to fields perpendicular to the z-axis of the crystal, three-dimensional full-vectorial measurements can be easily obtained by mounting three sensors in orthogonal directions.

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