Integrated optical modulators for high spectral efficiency

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Abstract—**Coherent modulation formats have gained considerable importance in high-capacity, high-efficiency optical systems. A key component for achieving good transmission performances are Lithium niobate modulators, which can be designed and optimized to operate with BPSK, QPSK, 16-QAM and OFDM modulation schemes providing excellent results.**

Keywords-LiNbO$_3$; coherent systems; modulators.

I. INTRODUCTION

Since the first introduction of WDM systems in the 1990's, fiber optic networks capacity have continuously increased their capacity in order to respond to the growth of data traffic. The two main pillars of this huge capacity expansion have been WDM (that is, wavelength division multiplexing) and fiber amplifiers (e.g., EDFAs), while the dominant transmission format was IMDD (intensity modulation with direct detection). However, the principle of wavelength multiplexing has been fully exploited and the spectral limit of the optical amplifiers has been reached by packing up to 80 channels with 50 GHz spacing. Increasing the channel data rate up to 40 or 100 Gbps is not practically feasible with 50 GHz channel spacing, since strong crosstalk is present between adjacent channels. Moreover, at these bit rates, dispersion and PMD have a significant impact on transmission performances.

These limitations can be efficiently overcome with new modulation formats based on the phase of optical signals. In this case, the modulation is not simply on-off (intensity based), but based on phase changes as well, and it can be binary, quaternary, or even more complex. Modulation formats such as differential phase shift keying (DPSK), or differential quadrature phase-shift keying (DQPSK), are already present in commercial transmission systems with excellent results [1].

Using higher-level modulation schemes plus coherent detection, electronic DSP are capable of eliminate impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD), extending the maximum reach of the systems considerably. A further advantage is to multiplex two orthogonal polarizations of the optical signal:. Polarization Division Multiplexing (PDM or simply PM), devices are becoming very useful in recent long-haul coherent systems, in combination with polarization-diversity receivers. The higher level formats allow to "pack" a given data rate into a lower data rate (e.g., in case of 100G, the modulators work at 25 Gbaud, while the aggregate data rate is 100Gbps. Thus, strong increase of the spectral efficiency can be achieved [2], [3]. On the component side, the requirements on laser sources and other components have become more stringent, and all-optical generation of these new formats has justified a strong development effort for new modulators capable of working with complex, multilevel and even polarization-multiplexed signals. [4], [5].

Lithium niobate technology is considered quite "mature" [6], yet it has already supported the introduction of many important breakthroughs in network capacity and spectral efficiency. These devices were first introduced into the first 2.5Gbps systems, passing to 10 Gbps WDM systems and then supporting 40G RZ-DPSK and DQPSK transmission in a well-established class of new commercial systems. Recently, new evolutions of LiNbO$_3$ modulator architectures have opened the way to a innovative, efficient and reliable multilevel coherent transmitter. The high extinction, broad-bandwidth and low driving voltage of LiNbO$_3$ devices allow generation of clean and undistorted signal constellations in QPSK, 16QAM and more complex configurations such as multicarrier and OFDM [7], [8], [9].

In this paper, we review some of the main characteristics of multilevel optical modulators for coherent formats, putting in evidence the limitations, perspectives and challenges of such devices on the Lithium niobate platform.

II. MODULATOR SCHEMES

A. *Basic building blocks*

The most common Lithium niobate intensity modulators used in practical optical communication systems are based on the Mach-Zehnder Interferometer (MZI). The optical structure consists of a couple of parallel phase modulators plus a splitter and a combiner sections which transforms an RF signal into an intensity modulation of a CW laser signal.

The introduction of four-symbol modulation formats such as (D) QPSK has brought into modulator's product lines the so-called "dual parallel" or I-Q MZI [8]. This device can produce 4 complex signals (module and phase are necessary to characterize each of them), and it becomes in turn the building block for 8-PSK, 16-QAM, 64-QAM [9] and more. Due to the complex signal constellations required in M-PSK and M-QAM formats, there are several options for generating the same configuration. In some cases, the I-Q modulators can be cascaded and combined with a predefined attenuation [8], [9] to achieve the desired amplitude and phase, or they can be cascaded, including in some cases also phase modulators [10]. Among the recently developed coherent formats, the multicarrier approach has attracted considerable attention: OFDM in particular is widely considered as the most promising technique. This format requires not only complex modulation, but also optical filter functions such as interleavers for separating the optical subcarriers [5].

The basic building blocks required for integration of higher order modulation formats are already available within Lithium niobate technology, and in principle all the passive devices can be allocated on the same substrate. Nevertheless, there are drawbacks due to the shallow contrast of the waveguides, and some hybrid integration solutions provided interesting results.

B. Cascading and integration issues

Despite its simple concept, QPSK devices must be very carefully optimized in order to achieve high extinction ratios and precise 90° phase shift between the 4 symbols. The basic building blocks (splitters, couplers, etc.), even if robust when working in simple configurations, might not be to suitable for the stringent requirements of coherent transmission, thus optimization must be performed on the whole structure to ensure that all optical paths are balanced. Generally speaking, a complex cascade of curves, splitters, couplers and I-Q modulators implies careful design of filtering sections to get rid of any unwanted coupling of radiated waves into adjacent devices. The cascade also brings in more extra losses, which must be kept as low as possible to limit the need for optical amplification in the transmitter. Moreover, the spurious chirp generated inside the amplitude modulators, in particular, is detrimental to the transmission performances, and it must be tightly controlled through electro-optic sections design.

Moreover, in real system design, the devices must have photo-detectors, which must be then integrated with the modulator chip inside its package. These PD's have much more stringent requirements than in simpler devices in order to set the operating bias point and keeping it stable over time and temperature, and in some formats such as DQPSK they can also be required to be broadband up to 1 GHz.

C. Polarization Multiplexing: issues and challenges

Another "modulation dimension" can be added, as it was mentioned before, by using orthogonal polarizations that share the same optical fiber without disturbing each other during propagation. Lithium niobate devices are strongly birefringent and have their maximum electro optic efficiency only on TE or TM polarization (depending on the wafer cut): as a consequence, the two polarization channels must be modulated in the same state and eventually rotated. This step can be done either by a polarization rotator and combiner realized with PLC with a wave plate [9], or by an integrated polarization rotator and combiner directly on $LiNbO_3$, (even if it requires much more space on the chip). The wave plate has been already used successfully in passive PLC components, such as the AWG.

III. SIZE REDUCTION: HYBRID APPROACH

One key point of optical integration is size reduction. Lithium niobate modulators are several cm long, in order to get low driving voltages and low power consumption. Because of the additional optical building blocks, multilevel devices can become exceedingly large due to the shallow curves which can be fabricated on this substrate to keep propagation losses low. Hybrid integration with silica-based PLCs is an enabling technology which reduces the chip size on Lithium niobate 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).

Taking this approach to the extreme consequences, one could think of putting on the LiNbO3 substrate only phase modulators, while all splitters and combiners sections are cascaded on PLCs. Part of the benefits which come from this approach, are paid in terms of higher insertion loss and more complex alignment processes but, on the other hand, a given nested structure can be coupled with different PLC pairs in order to get different modulation formats [9], [10].

IV. CONCLUSIONS AND DISCUSSION

Lithium niobate technology remains a key building block of coherent transmitters. All the most advanced modulation formats such as multicarrier, OFDM and coherent QAM, benefit from the electro-optical characteristics of $LiNbO_3$ devices, whose performances are still unsurpassed for long-haul transmission. The challenge of new multilevel optical transmission has brought into development and production new hybrid integration techniques, which will allow further evolution and scalability of the networks.

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