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# Integrated Photonic Devices Driven by Surface Acoustic Waves

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**Abstract**

A compact tunable photonic modulator driven by surface acoustic waves in the GHz frequency range is reported. The device follows a well-known Mach-Zehnder interferometer structure with three output channels, built upon multi-mode interference (MMI) couplers. The light continuously switches paths between the central and the side channels, avoiding losses and granting a 180°-dephasing synchronization between them. The modulator was monolithically fabricated on (Al,Ga)As, and can be used as a building block for more complex photonic functionalities. Light modulated at multiples of the fundamental acoustic frequency can be accomplished by adjusting the applied acoustic power.

A great effort has been made during the past decades to increase the integration level in photonic circuits. Although integration levels of up to a few hundreds of components per chip have been accomplished, photonic integrated circuits are still far from reaching the same development followed by its electronic counterpart. The search for solutions that allow devices that are at the same time fast, compact, inexpensive, and compatible with nowadays integration technology is of paramount importance. The external control of light propagation inside the devices allows for a reduction in the dimensions, favouring the integration and giving rise to novel functionalities. A promising approach consists of using a surface acoustic wave (SAW) to modulate single or multiple ridge or slot waveguides through the acousto-optical effect, with the possibility of adressing several devices with the same SAW beam. This method presents an excellent compromise between speed and size, and can be implemented in almost any material platform such as Silicon, (In,Ga)P or $LiNbO_3$. In this contribution, we will address the design, fabrication, and characterization of a three output photonic modulator driven by surface acoustic waves in the GHz frequency range, in which the light is continuously splitted, with a 180° - dephased synchronization, between the central and side waveguides. This is in contrast with most of the previous works, which explored designs with a single output [1]–[3] or, very recently, two outputs [4].

The device consists of a Mach-Zehnder interferometer (MZI) structure with three output waveguides, built upon multi-mode interference (MMI) couplers with the same coupling length [Fig. 1(a)]. The first coupler is a balanced (50:50) splitting ratio MMI that splits the incoming light into two identical optical beams which are then modulated by a SAW beam propagating perpendicularly to them ($MWG_1$ and $MWG_2$). The SAW beam is generated by an interdigital transducer (IDT). A second MMI coupler combines the input light into three output waveguides ($OWG_L$, $OWG_C$ and $OWG_R$) with different power distribution depending on the phase and intensity of the light coming from the active region of the device. The spatial separation between the waveguides in the active region must be set to $(2m + 1)\lambda_{SAW}/2$, where $\lambda_{SAW}$ is the surface acoustic wave wavelength, and $m$ is an integer. This ensures that each of the MWGs suffers a change in the effective refractive index of equal magnitude but opposite phase, maximizing therefore the acousto-optical modulation.

The response of the device was simulated using a finite difference beam propagation (BPM) method implemented via the RSoft package. Assuming either the transverse electric (TE) or the transverse magnetic (TM) polarizations at the input waveguide, we tracked the propagation of the optical field throughout the device. The width and length of the MMI couplers in the devices were optimized to operate at 900 nm. The device was fabricated on a sample grown by molecular beam epitaxy on a (001) GaAs wafer. The sample consists of a 300-nm-thick GaAs film forming the guiding layer, deposited on a 1500-nm-thick $Al_{0.2}Ga_{0.8}As$ buffer layer. The modulator was fabricated in two steps using contact optical lithography. First, Ti/Al/Ti IDT in a split finger configuration for efficient SAW generation was fabricated using a lift-off process. The IDT was designed for

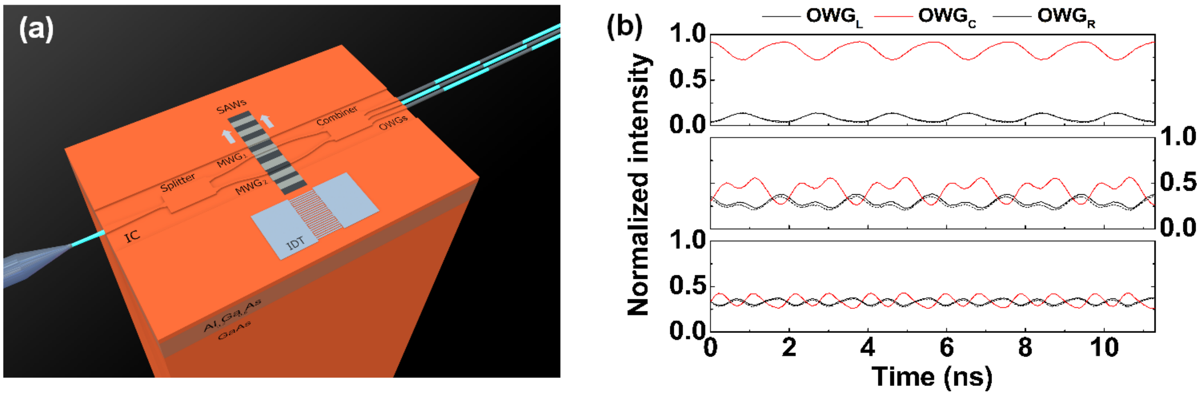


Fig. 1. *(a) Illustration (not to scale) of the SAW-driven Mach-Zehnder interferometer with three output waveguides, fabricated on (Al,Ga)As. (b) Time-resolved traces recorded for the light leaving the OWG*$_{\rm L}$ *(dotted black line), OWG*$_{\rm C}$ *(solid red line) and OWG*$_{\rm R}$ *(solid black line), measured for the TE polarization and RF powers of* $P_{\rm IDT} = 6.8$ *mW (upper panel),* $P_{\rm IDT} = 68.3$ *mW (central panel), and* $P_{\rm IDT} = 108.3$ *mW (bottom panel).*

an operation wavelength of $\lambda_{\rm SAW} = 5.6$ $\mu$m [5] (corresponding to a resonance frequency of approximately 520 MHz), with finger width and spacing of 700 nm. A second step of plasma etching was employed to create the 137-nm-deep grooves delimiting the rib waveguides of the device.

The device was optically characterized by coupling light into the input waveguide using a tapered optical fiber probe with a lensed tip. As light source, we used a superluminescent diode with peak emission centered at the wavelength $\lambda = 920$ nm, with a full width at half maximum of approximately 40 nm. The transmitted light was detected using a Si avalanche photodiode with a time resolution of 500 ps, synchronized with the RF signal driving the IDTs. Time-resolved transmission traces were recorded for different RF powers ($P_{\rm IDT}$) applied to the IDT, and light with TE polarization (similar behavior was observed for light with TM polarization). The total transmission is normalized to 1. At small $P_{\rm IDT}$ [Fig. 1(b), upper panel], the light is modulated at the SAW fundamental frequency ($f_{\rm SAW}$), with the central waveguide contributing to nearly 80% of the total transmission. When $P_{\rm IDT}$ increases, the presence of higher harmonics becomes evident. At $P_{\rm IDT} = 68.3$ mW [Fig. 1(b), central panel], the modulation at the first harmonic is less intense with a simultaneous increase in the modulation at the second harmonic. At $P_{\rm IDT} = 108.3$ mW [Fig. 1(b), bottom panel], the light modulation is entirely dominated by the second harmonic.

In conclusion, we have developed an acoustically driven photonic modulator based on a Mach-Zehnder interferometer that operates in the GHz range. The lateral channels are 180°-dephased with respect to the central one, whose phase and amplitude response can be changed by varying the applied acoustic power. The device was monolithically fabricated on (Al, Ga)As, although it can be easily implemented in other material platforms (InP, $LiNbO_3$), or even in non-piezoelectric materials, such as Si. In this case, SAWs can be generated by IDTs placed on a piezoelectric overlayer. Modulation at the second harmonic of the SAW driving frequency (1.03 GHz) is accomplished. The large phase coherence of the surface acoustic waves allows for the modulation of several ridge or slot waveguides using the same acoustic beam. The modulator can be used as a building block for more complex photonic functionalities. This research has been supported by the Spanish MINECO Projects TEC2010-21337 and MAT2012-33483. Financial support through FPI grants BES-2010-036846 and BES-2011-046100 is gratefully acknowledged.

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