Compact acousto-optic multimode interference device in (Al,Ga)As

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Abstract: Multimode interference (MMI) devices are key components in modern integrated photonic circuits. Here, we present acoustically tuned optical switches on an (Al,Ga)As platform that enable robust, compact and fast response systems improving on recently demonstrated technology. The device consists of a $2 \times 2$ MMI device fine-tuned in its center region by a focused surface acoustic wave (SAW) beam working in the low GHz range. In this way, we can tune the refractive index profile over a narrow modulation region and thus control the optical switching behaviour via the applied SAW intensity. Direct tuning of the MMI device avoids losses and phase errors inherent to arrayed waveguide based switches, while also reducing the dimensions of the photonic circuit.

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1. Introduction

Modern day optical communication systems rely increasingly on compact solutions to manage the data throughput at signal processing interfaces. To this end multimode interference (MMI) devices have become a crucial building block in the design of complex photonic integrated circuits (PICs). Thus, they are subject to thorough investigation that has its sights set on making them rapidly tunable while also maintaining their compact size.

Recent works towards this direction make use of the electro-optic effect that enables switching between the MMI device’s output ports with frequencies in the GHz range [1]. To control the refractive index modulation inside the MMI device, electrodes are placed on top of the optical circuit structures to reconfigure the device response via current injection. This works well for piezoelectric materials, resulting in a device footprint of a few millimetres, but is demanding in terms of fabrication [2–4].

Other investigated approaches make use of the thermo-optic effect to create small Mach-Zehnder interferometer (MZI) switches in silicon on insulator systems [5,6]. Recently, more robust devices were established by placing electrode heaters directly on a MMI device [7,8] or injecting currents at the lateral regions that heat up selected areas of the device, allowing for discrete tuning of the effective refractive indices of the modes travelling therein [9]. Depending on the material system used, these solutions can make way for compact devices, albeit the limitations associated, like slow response times in the µs range, have yet to be overcome.

In this work, we therefore propose the use of the acousto-optic effect for the tuning of the MMI device. On piezoelectric materials, surface acoustic waves (SAWs) can be excited by interdigital transducers (IDTs) deposited on their surface [10]. The SAW frequency $f_{\text{SAW}}$ depends on the periodicity $p$ of the comb-like interdigitating finger structure and can be expressed by $f_{\text{SAW}} = c_{\text{SAW}}/2p$. Here, $c_{\text{SAW}}$ is the SAW phase velocity, which is around 3000 m/s for GaAs. The mechanical strain field of the SAW induces a dynamic elasto-optic modulation of the refractive index profile of the material surface region [11]. This makes SAWs a very effective tool for...
the modulation of PICs with rib/ridge waveguides or guiding layers embedded within about a distance of one acoustic wavelength \( \sim \lambda_{SAW} \) below the material surface. Experimentally, the application of a SAW in a MZI waveguide system has been first reported by Gorecki et al. [12]. In following research the acousto-optic modulation of PICs has been further established and proved to be an excellent combination to achieve compact and increasingly complex system designs with fast response times in the low GHz range [11,13–16]. In these prior devices an array of photonic waveguides was introduced between the MMI devices in order for the acoustic tuning to be effective. With our proposed design we can omit the array by using focusing IDTs (FIDTs) to create an intensive, narrow SAW beam for the direct tuning of selected areas of the MMI device, resulting in more compact devices [17,18]. With the omission of the array waveguides the device additionally becomes less susceptible to phase errors and losses that would result from the narrower and curved singlemode waveguide structures. Additional design changes include the increase of the optical free space wavelength from \(~900\text{ nm}\) to around \(~1550\text{ nm}\), in order to make the devices more suitable for the use in state-of-the-art telecommunication technologies. Further corroborating the versatility of acoustic waves, the interaction between light and sound has recently been exploited in suspended structures for Brillouin scattering for optical beam steering [19] and the realization of an acousto-optic gyroscope [20].

2. Design

The devices are designed to be monolithically fabricated on an (Al,Ga)As system consisting of a 200 nm thick GaAs substrate, a 2500 nm thick Al\(_{0.3}\)Ga\(_{0.7}\)As buffer layer with a 500 nm thick GaAs guiding layer grown on top. The guiding region of the PIC consists of a 500 nm high ridge waveguide structure embedded in a 250 nm high slab. This results in a 0.5 slab to waveguide height ratio, which assures good efficiency of the acousto-optical modulation [21], while also confining the 1550 nm light signal within the circuit geometries. At its heart, the PIC consists of a 2 × 2 MMI device of \( L_{MMI} = 1190 \mu\text{m} \) length and a width \( W_{MMI} \) of 11.2 \( \mu\text{m} \) that operates on the basis of the self-imaging principle of its input signal [22]. The two input and output tapered waveguides are positioned at 4.2 \( \mu\text{m} \) from the center of the MMI device. The tapered waveguides are 2.6 \( \mu\text{m} \) wide at their connecting point to the MMI device and adiabatically taper off, over 100 \( \mu\text{m} \), into 1.2 \( \mu\text{m} \) wide single-mode waveguides. To facilitate the measurements of the PIC three additional design steps are taken. First, the waveguides are spatially separated by 28 \( \mu\text{m} \) from each other via s-bends with large bending radii. A slight off-set of the s-bend in the \( x \)-direction is introduced at the junction between either end of the s-bend and the respectively linked waveguide, in order to minimize optical transition losses between the two structures [23]. Second, the waveguides then also taper off into 4 \( \mu\text{m} \) wide input or output waveguides at the edges of our sample, where the light is coupled in or out, respectively. Third, the devices are designed symmetrically so that the input and output waveguides can be used interchangeably by rotating the sample 180° in its \( xz \)-plane. Perpendicular to the optical beam propagation we apply a SAW that is focused on the center region of the MMI device. This can either be a travelling SAW as depicted in Fig. 1 or a standing SAW, which has the benefit of enhanced acousto-optic interaction and will be discussed in the experimental section. In either case, the SAW introduces a modulation of the refractive index profile with amplitude \( \Delta n \) given by [14]:

\[
|\Delta n| = \frac{a_p\lambda}{2\pi l}\sqrt{P_{SAW}}. \tag{1}
\]

In this equation, \( l \) is the length of the acousto-optic modulation region, \( \lambda \) is the light wavelength, \( a_p \) is a proportionality constant depending on the material properties as well as on the acousto-optic interaction mechanism and \( P_{SAW} \) is the nominal power of the SAW. The change of the refractive index generates a phase change \( \Delta \phi \) in the light signal passing through the modulation region, which is related to the SAW power by \( \Delta \phi = a_p\sqrt{P_{SAW}} \). For the best modulation efficacy, the
position of the access waveguides and the width of the MMI device must be chosen in accordance with $\lambda_{\text{SAW}}$ to ensure that each self-image undergoes a phase shift of opposite sign $(n_0 \pm \Delta n)$ for a given SAW phase. In a $2 \times 2$ MMI device, this is achieved when the self-images are separated by $\Delta x = (2m + 1)\lambda_{\text{SAW}}/2$, where $m$ is an integer [14].

For the acoustic modulation, a double-finger FIDT is placed $56\,\mu\text{m}$ away from the MMI device’s center. The FIDT design is taken from [17] in order to create a SAW wavelength $\lambda_{\text{SAW}}$ of $5.6\,\mu\text{m}$ with a minimal beam waist of $18\,\mu\text{m}$ that tunes the refractive index of the MMI device with little attenuation along its width.

Fig. 1. Sketch of the designed $2 \times 2$ MMI device tuned by a surface acoustic wave excited by a focusing interdigital transducer (FIDT). A straight tapered lensed fiber couples the signal laterally into the guiding layer of the GaAs/Al$_{0.3}$Ga$_{0.7}$As/GaAs material structure. The signal passes through a single-mode waveguide into the MMI device, where the SAW modulates the refractive index of the center region. As a result, the signal oscillates between the two output waveguides. Dimensions are not to scale.

The design is easily expandable to symmetrical $N \times N$-MMI devices with $N \geq 2$ (where $N$ is an even number of entrance/exit waveguides spaced equidistantly from each other along $W_{\text{MMI}}$) as long as

$$L_{\text{MMI}} = P\left(3L_\pi/4\right) \quad (2)$$

is satisfied, where $P > 0$ is an integer [22]. If $P$ is chosen to be an odd number, the input field will be mirrored with respect to the $xy$-plane at the end of the MMI device. Otherwise, the input field will be reproduced as a direct self-image. $L_\pi$ is denoted as the beat length of the MMI device and is defined through

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_{\text{eff}}W_e^2}{3\lambda_0}, \quad (3)$$

with $n_{\text{eff}}$ the effective refractive index, $\beta_0$ and $\beta_1$ the propagation constants of the fundamental and the first order modes of the multimode region. $W_e$ is the effective MMI device width, which takes the Goos-Hänchen-shift into account [24]. The effective refractive indices can be calculated with the effective index method [25]. Refractive index values for GaAs and Al$_{0.3}$Ga$_{0.7}$As for the used optical wavelengths and at room temperature are taken from [26] and [27], respectively.

The devices can be understood as the combination of two MMI couplers (MMIC) of equal length $L_{\text{MMIC1}} = L_{\text{MMIC2}} = 3L_\pi/2$ with an even number of $N$ access waveguides. Two self-images are created in the region where the two MMI couplers are connected. The SAW will be focused on this junction. For each of the $N$ input waveguides, the two self-images are separated by a
distance \( d = \frac{\lambda_{\text{SAW}}}{2} + m\lambda_{\text{SAW}} \), with \( m \) an integer, ensuring that they are modulated with opposite phase as in the previously reported MMI devices with two modulated waveguides \([14,28]\). The modulated optical signal will switch paths between the pre-set exit waveguide and an adjacent one for different phases of the SAW. Furthermore, a general method to calculate the transmission of an arbitrary \( N \times N \) device can be achieved by following the photonic router design procedure laid out in detail in \([29]\). For the case of a single MMI device this can be realized by choosing \( P = 1 \) and omitting the array arm phase shift with \( \Phi_{\text{arms}} = 0 \).

The position of the FIDT aperture center in relation to the MMI length can generally be expressed as follows:

\[
z_{\text{FIDT}_j} = L_{\text{MMI}} \frac{(2j - 1)}{2P} \quad \text{with} \quad j = 1, \ldots, P.
\]

In our case we chose the shortest MMI length with \( P = 1 \) so that the FIDT is focused on the MMI center at \( z_{\text{FIDT}_1} = \frac{L_{\text{MMI}}}{2} \).

3. Simulations

To explain the above chosen dimensions and parameters of our design we will take a closer look at the optical signal propagation and acousto-optical interaction via the beam propagation method (BPM). The simulations were run on commercial software packages.

The simulations conducted for a passive MMI device are displayed in Fig. 2(a). In the passive device a 1550 nm signal is launched into input port \( i = 1 \) and finds its mirror image at the opposite waveguide exit \( k = 2 \). Figure 2(b) shows the active device with a SAW launched perpendicularly

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**Fig. 2.** (a) Optical field amplitude through the passive MMI device with the 1550 nm light entering the first input waveguide labelled \( i = 1 \) and producing a mirror image at the opposed waveguide exit \( k = 2 \). (b) Simulation of the optical amplitude distribution in a SAW tuned device. Here, the interference pattern is driven to reproduce the entrance signal at output \( k = 1 \). (c) Zoom-in on the center region of the MMI device experiencing refractive index modulation through the applied SAW beam. The two self-images of the input signal are \( \Delta x = 1.5 \lambda_{\text{SAW}} = 8.4 \, \mu\text{m} \) apart. \( l \) represents the length of the acousto-optic modulation region. (d) Superimposed plot of the calculated refractive index modulation (red) and the optical propagation intensity (black) traversing the waveguide at cross-section \( z = \frac{L_{\text{MMI}}}{2} \).
to the optical field transmission direction. Based on diffraction theory [30,31], the simulation considers a modulation of the refractive index profile in $z$ direction according to the first spherical Bessel function $j_0(x) = \sin(x)/x$. This dependence of the focused SAW field propagation was proven to reproduce measurement data well [17]. In $x$ direction a $\cos(x)$ dependence was assumed. Combining the refractive index profiles in both directions the complete modulation function is given by

$$n(x, z) = n_0 + \Delta n \cos \left( k_{\text{SAW}}x + \frac{\pi}{2} \right) j_0 \left( \frac{k_{\text{SAW}} \Phi}{2(1 - 2a)} z \right).$$

(5)

Here, $a$ is the acoustic anisotropy parameter that has to be considered for SAWs travelling in GaAs and $\Phi$ is the aperture angle of the FIDT, $k_{\text{SAW}} = 2\pi/\lambda_{\text{SAW}}$ is the wavenumber, $n_0$ is the unperturbed refractive index for GaAs at the optical design wavelength $\lambda_0$. The full width at half maximum (FWHM) of the SAW beam profile is simulated to be 20 $\mu$m wide in the MMI device enabling us to finely tune the refractive index profile in the area of the two self-images of the input signal that are produced around $L_{\text{MMI}}/2 \pm (\sim 20 \mu$m), as shown in Fig. 2(c). Because of the MMI device’s good operational tolerance the acousto-optic tuning works over a wide optical bandwidth [32]. Figure 2(d) shows the modulation of the refractive index profile along the $x$-axis at $L_{\text{MMI}}/2$ superimposed with the optical field amplitude for a modulation amplitude $\Delta n = 0.0125$. Due to a spatial separation of $\Delta x = 1.5\lambda_{\text{SAW}}$, each self-image is modulated with an opposite acoustic phase in order to enhance the acousto-optical interaction. The switching between the channels then occurs at twice the SAW frequency $f_{\text{SAW}}$, since the maximal difference between the refractive index modulation of each image is achieved twice per SAW period $T_{\text{SAW}}$.

4. Experimental setup

Figure 3 shows the setup of the experiment. The measurements of the samples are conducted using a diode laser producing the light signal tunable around 1550 nm. The signal is coupled into a single-mode fiber terminating in a straight tapered lensed tip that then couples the light into the device’s input waveguides $i$. At the end of the sample we place a mirror that reflects the signal coming out of the output waveguides $k$ by 90° into a 20x microscope objective. The signal then passes through a polarizer to select either the TE or the TM modal response. Next, a 50:50 beamsplitter directs half of the optical signal to a charged-couple device (CCD) camera optimized for infrared measurements. The other beamsplitter output is coupled into a multimode fiber connected to an InGaAs photodetector with a 5 GHz bandwidth or an optical power meter. The photodetector is then connected to an oscilloscope and the power meter to a computer, where the measurement data is recorded and stored.

In the acoustic part of the measurement setup we use a network analyser to characterize the transmission and reflection properties of the FIDTs and identify the exact resonance frequency $f_{\text{SAW}}$, which for our device was found to be around $(522 \pm 1)$ MHz. In order to test our device under the influence of a standing SAW, the RF signal is first split right after it leaves the generator. On one side the signal then passes through a phase shifter that enables us to fine-tune the interference between the two SAWs, offering another degree of acousto-optic tunability. The signal is then amplified before its application at the FIDT via a probe tip. In the second arm of the rf-circuit the signal is attenuated to compensate for the losses the first signal experiences at the phase shifter. The second signal is then also amplified before being applied to the second FIDT.
Fig. 3. Experimental setup: The light signal from a laser diode is coupled into the sample input waveguide \( i \) via a lensed fiber. A mirror reflects the outgoing signal from output waveguide \( k \) by 90° into a microscope objective that is placed over the device under test (DUT). The optical signal then passes through a beamsplitter and is simultaneously observed with a CCD camera and measured with a fast photodetector or a powermeter. A signal generator is used to provide the radio frequency (RF) signal with the appropriate frequency and power to excite one or both of the FIDTs. The acoustic setup allows the creation of a standing SAW in the DUT by using an adjustable phase shifter connected to the first FIDT and an adjustable attenuator to the second one.

5. Results

In a first step, the PIC was fabricated monolithically on a (Al,Ga)As system discussed in detail in Sec. 2. To minimize sidewall roughness, the waveguides were processed via e-beam lithography followed by plasma etching. In a second step, the Ti/Al/Ti FIDTs were fabricated via optical lithography and a lift-off process.

A micrograph and a SEM image of the resulting devices can be appreciated in Fig. 4(a) and (b), respectively. The design footprint of the complete device composition with two FIDTs and two 2 × 2 MMI devices between them is (3 mm × 6 mm). The active modulation region between the two FIDTs is, however, only (193.2 µm × 30 µm). In Fig. 4(c) the cross-section of an output waveguide can be seen from a frontal view of the device. The effective etch depth of the sample was found to be around 200 nm. During the measurements the slightly slanted sidewalls and minor etch roughness visible in the images was found to not impact the functionality of the MMI device in a significant way. The change of the optical response to a surface acoustic wave was recorded with the infrared CCD camera and can be appreciated in Fig. 4(d) for both the passive
MMI device at $P_{\text{SAW}} = 0 \text{ mW}$ and the SAW tuned device at $P_{\text{SAW}} \approx 31 \text{ mW}$. When the SAW is turned on, the signal switches periodically between the two output waveguides. In the camera images one can clearly observe that part of the light intensity is shifted from one channel to the other.

![Micrograph of two of the fabricated 2 × 2 MMI devices. Two FIDTs generate a standing SAW within the indicated modulation region.](image)

![SEM image of the end of the MMI device and the connecting tapered output waveguides.](image)

![Frontal view of the left side of an exit waveguide at the sample edge.](image)

![Infrared CCD camera images of the optical response for a passive state MMI device ($P_{\text{SAW}} = 0 \text{ mW}$) and a SAW tuned MMI device ($P_{\text{SAW}} \approx 31 \text{ mW}$).](image)

**Fig. 4.** (a) Micrograph of two of the fabricated 2 × 2 MMI devices. Two FIDTs generate a standing SAW within the indicated modulation region. (b) SEM image of the end of the MMI device and the connecting tapered output waveguides. (c) Frontal view of the left side of an exit waveguide at the sample edge. (d) Infrared CCD camera images of the optical response for a passive state MMI device ($P_{\text{SAW}} = 0 \text{ mW}$) and a SAW tuned MMI device ($P_{\text{SAW}} \approx 31 \text{ mW}$). In both cases light is coupled in at input 1.

The optical intensity profiles of a TE polarized light signal at the two output ports are shown in Fig. 5(a) for increasing SAW intensities $P_{\text{SAW}}$. Here, a 1547 nm light beam is coupled in through channel $i = 1$. In order to adequately estimate $P_{\text{SAW}}$, the scattering parameters of the FIDTs were characterized before each measurement using a network analyser and the losses through the RF circuit were carefully addressed. The traces are normalized to the maximum value of both signals. The output ratio between the two channels against increasing SAW power is plotted in Fig. 5(b). The device switches from the pre-set cross coupled state without a SAW, towards a split state for 31.39 mW. Here, the time integrated gain at output port 1 reaches 2.2 dB and the extinction ratio at output port 2 reaches $-2.63$ dB. A 3 dB coupling state is almost reached, but limited by the maximum input power to the FIDTs. At this point it is expected that switching between both outputs would reach 100% with the light spending half of the acoustic period $T_{\text{SAW}}$ in one output channel, before switching to the other output channel for the remaining half of $T_{\text{SAW}}$. This could be achieved by an increase of the acousto-optical coupling, therefore wider SAW beam waists are proposed for future devices. The optical insertion loss is estimated to be
∼20 dB. The MMI device’s symmetry allows it to be driven in both directions, i.e. output ports can be used as input ports and vice versa.

Figures 6(a)–(c) show the recorded and simulated (solid curves) TE-polarized light intensity oscillations along one SAW period \( T_{\text{SAW}} = 1.91 \text{ ns} \) for different \( P_{\text{SAW}} \). The total transmission intensities are normalized to 1 for each measurement and its respective simulation. At low rf power \( P_{\text{SAW}} = 4 \text{ mW} \) slight signal modulation can already be observed in both channels.

Further increasing the acoustic modulation then drives the responses towards higher time resolved extinction ratios. As can be seen for \( P_{\text{SAW}} = 15.74 \text{ mW} \), the peak-to-peak amplitudes of both signals have almost tripled as compared to the prior SAW power. At this point an amplitude imbalance between both outputs of about ∼20% is measured, with the signal amplitude in the preset output 2 being the dominant one. The imbalance is reduced to ∼14% at \( P_{\text{SAW}} = 31.39 \text{ mW} \), while the peak-to-peak amplitudes in both channels have increased by a factor of four in comparison to the amplitudes at \( P_{\text{SAW}} = 4 \text{ mW} \). Independent of the SAW intensity, the modulated signal is selected by its preset, passive state twice per period when the standing SAW reaches 0 amplitude in its anti-nodes. Analogously, the light is selected by the other channel when the standing SAW peak-to-peak amplitude reaches its maximum. With increasing SAW power the light maximal intensity measured at channel 1 rises steadily. At \( P_{\text{SAW}} = 31.39 \text{ mW} \) two thirds of the optical signal are directed from output channel 2 to output channel 1. At these instances the 180° phase shift between the two channel responses can be clearly observed. The occurrence of unwanted frequency modulations caused by phase errors as reported to occur in array waveguides [15] are not discernible in the compact MMI device response. The observed channel imbalances and optical losses are mainly attributed to deviations from the design slab height and sidewall roughness.

The recorded experimental time-resolved traces match the calculations made for \( \Delta n = 0.0045, 0.009 \) and 0.0125 closely. Here, the measured etch film thickness of 200 nm is considered. The simulation results are represented by the solid plot lines in Figs. 6(a)–(c). Increasing the SAW intensity in the simulations beyond that achieved in the experiment, we can predict the 3 dB coupling state of the device at a refractive index modulation amplitude of \( \Delta n = 0.0148 \). From the theoretical model one can then infer an acoustic power level of >45 mW to achieve 50/50 switching in the experiment.

Finally, using Eq. (1) the figure of merit \( a_p \) for our device is calculated to be ∼ 0.129 rad/√mW.

From this a good degree of acousto-optic interaction can be inferred. In comparison to past devices it doubles the \( a_p \) value reported for the same FIDT design, but for \( \lambda = 900 \text{ nm} \) [14].
Fig. 6. (a)–(c) Time response of the output channels for $P_{\text{SAW}} = 4 \text{ mW}$, 15.74 mW, 31.39 mW, respectively. The SAW period is $T_{\text{SAW}} = 1.91 \text{ ns}$ long. Dots represent measurement data, lines the corresponding simulation calculated for refractive index amplitudes $\Delta n = 0.0045$, 0.009 and 0.0125, with respect to the panel sequence (a)–(c).

It is approximately the same as the one reported for a non-focusing double-finger IDT with an acousto-optic interaction length of 120 $\mu$m and the same acoustic wavelength, but also for a light wavelength of $\lambda = 900 \text{ nm}$ [28].

While in our experiment only two MMI devices lie between the two FIDTs (compare Fig. 4(a)), it is in general possible to tune many more parallel MMI devices by only one to two FIDTs. This is because of the low attenuation of the SAW, which is about 5% over more than 1000 $\mu$m propagation distance [17], as compared to the relatively short MMI width of $\approx 10 \mu$m. This makes the device a good candidate compatible for the integration within complex photonic circuits with functionalities such as lasers, switches or wavelength multiplexing devices.
6. Conclusion

A compact acoustically tunable MZI design based on MMI devices and FIDTs is presented and analysed for light signals in the telecommunication wavelength range. It is found to be a viable improvement in compactness of the PIC over prior devices based on arrays of waveguides used to achieve similar results. The working principle can easily be extended from $2 \times 2$ MMIs to $N \times N$ MMIs for two channel switching. However, making three or more channels available for the dynamic tuning imposes further challenges on the FIDT design and application. The MMI devices presented here can be driven using only one FIDT creating a travelling SAW. The acousto-optical interaction is, nonetheless, limited by the short optical signal spot size. This challenge was overcome by applying a standing SAW created through two opposing FIDTs of identical design. With the thus amplified SAW power and the resulting increase of the refractive index modulation a clear tuning of the optical response could be observed. In future devices one can also use single-finger FIDTs to create an acoustic cavity that confines the SAW and, thus, reach higher modulation levels and reduced power needs.

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