Acoustic phonons for coherent photon control in semiconductor structures

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Abstract.
We present a novel concept for acousto-optical modulation in waveguide (WG) structures using coherent phonons in the form of surface acoustic waves (SAWs). Here, a SAW impinging perpendicular to a waveguide structure induces a change in phase of the light propagating through it, which is translated into a transmission intensity modulation by using the WG as an arm of a Mach-Zehnder interferometer (MZI). We show that the modulation becomes strongly enhanced if the SAW induces phase changes of opposite sign in the MZI arms. Very compact modulators with an interaction length between the optical and acoustic waves of approx. 15 µm have been fabricated using focusing acoustic transducers to generate narrow and intense acoustic beams. We show that the acoustic MZI concept can be extended to realize integrated on/off switches by using devices with several interferometer arms.

1. Introduction
Coherent acoustic phonons in the form of surface acoustic waves (SAWs) propagating on a semiconductor surface create a moving strain and a piezoelectric modulation of the underlying material. This modulation gives rise to new elasto- and electro-optic interaction mechanisms in nanostructures, which open ways for the realization of tunable photonic devices[1] as well as for the coherent control of carriers[2, 3], spins[4, 5], and excitons[6].

An important area of application of acoustic phonons comprises the control of photons. While carrier manipulation is primarily mediated by the piezoelectric field produced by the SAW, photon control takes place through the time and spatial modulation of the optical properties by the SAW strain field. The conventional structure for optical control is the Bragg cell, where the incident light is diffracted by the refractive index grating produced by an acoustic wave[7]. Semiconductor nanostructures have opened novel possibilities for enhancing the acousto-optical interaction and satisfying the required phase matching between the acoustic and optical waves. Examples are the new scattering configurations that become available in superlattice structures[8] as well as the use of optical microcavities to enhance the elasto-optic interaction[9]. Recently, we have shown that the acousto-optic interaction in microcavities becomes sufficiently strong to form a tunable photonic or polaritonic crystal with the acoustic periodicity λ_{SAW} and stop-band widths defined by the acoustic amplitude[10, 11]. In the case of
polaritons, the interaction is mediated not only by the strain but also by the SAW piezoelectric field.

With the advent of integrated optics, approaches have been sought after to implement the acousto-optic phase matching required for photon control in waveguide (WG) structures. Examples are the acoustically induced coupling between neighboring WGs [7] as well as the umklapp scattering in periodic photonic structures [12, 13]. In this manuscript, we describe a new approach for integrated acousto-optical devices based on the coherent modulation of WGs by a SAW. The implementation of simple modulators, which are based on the modulation of the arms of a Mach-Zehnder interferometer (MZI) by an acoustic beam, is introduced in Sec. 2. In Sec. 3, this concept is extended to MZIs with multiple arms. The corresponding structures, which are denoted acousto-optical multiple interference devices (AOMIDs), allow for the realization of a wide range of functionalities such as on/off switches, frequency multipliers, and pulse shapers [14].

![Figure 1](image)

**Figure 1.** (a) Modulation of a Mach-Zehnder interferometer by a SAW. A high modulation efficiency is achieved by displacing the WG arms along the SAW path by an odd multiple of half the SAW wavelength, thus leading to light phase shifts of opposite sign in the arms. (b) Micrograph of an acoustic MZI using focusing transducers (IDTs) on an (Al,Ga)As WG structure.

2. **Acoustic Mach-Zehnder Interferometers (MZI)**

The use of SAWs to modulate MZIs was first proposed by Gorecki et al. [15, 16], who introduced an optical modulator based on the change in refractive index (n) of one MZI arm by a SAW beam. As illustrated in Fig. 1, the strain field of a SAW impinging perpendicularly to the interferometer arms introduces a periodic phase modulation of the transmitted light given by

$$
\delta \phi(t) = \delta \phi_{\text{max}} \cos \omega_{\text{SAW}} t
$$

in each arm, where $\delta \phi_{\text{max}} = 2 \pi \delta n / \lambda_L$ is the phase modulation amplitude and $\delta n$ is the amplitude of the refractive index change induced by the SAW in a WG with length $\ell$. The SAW frequency and the optical wavelength are denoted by $\omega_{\text{SAW}} = 2 \pi f_{\text{SAW}}$ and $\lambda_L$, respectively. In the previous expression, it has been assumed that the WG width is much smaller than $\lambda_{\text{SAW}}$. By using the modulated WG as one of the arms of a MZI, the phase shift leads to a periodic intensity modulation of the transmitted light. More recently, de Lima, Jr. et al. [17] introduced a new design, where a single SAW simultaneously modulates the refractive index of both MZI arms with opposite phases. The latter is achieved by simply spacing the WGs by an odd multiple of the half acoustic wavelength $\lambda_{\text{SAW}}$, as shown in Fig. 1(a). The transmission of this structure is given by:
Figure 2. (a) MZI transmission as a function of time (horizontal scale) and rf-voltage applied to the IDT \( (V_{rf}) \). (b) Transmission for different \( V_{rf} \). The SAW period is equal to 1.92 ns. The amplitude of the higher harmonics is limited by the time resolution of the detection setup.

\[
T = \frac{I_0}{I_i}(t) = \frac{1}{2} \left\{ 1 + \cos \left[ 2\delta \phi_{\text{max}} \cos \omega_{SAW} t + \delta \phi_s \right] \right\},
\]

where \( I_i \) (\( I_0 \)) denotes the incident (transmitted) light intensity and the static phase shift \( \delta \phi_s \) accounts for differences in the optical length of the WGs. Since \( \delta \phi_{\text{max}} \) depends on the square root of the acoustic power density, the WG arrangement of Fig. 1(a) requires four times less acoustic power for a given phase modulation level than if just one arm is modulated.

The micrograph in Fig. 1(b) displays an acoustic MZI fabricated on a GaAs/(Al,Ga)As layer structure grown by molecular beam epitaxy on GaAs (100). The 700 nm-wide single-mode ridge WGs have been defined on the 300 nm-thick GaAs surface layer by optical lithography and plasma etching. The SAWs are generated by a focusing interdigital transducer (IDT) designed for \( \lambda_{SAW} = 5.6 \, \mu m \) (corresponding to an acoustic frequency \( f_{SAW} = 1/T_{SAW} \sim 518.5 \, MHz \)), which delivers an intense acoustic beam with a width of approx. only 15 \( \mu m \).

The gray-scale plot of Fig. 2(a) shows the transmission of a nominally symmetric MZI [similar to the one in Fig. 1(a) but using a conventional IDT] as a function of time (horizontal axis) and amplitude \( V_{rf} \) of the nominal radio-frequency (rf) voltage applied to the IDT, which is directly proportional to the phase modulation amplitude \( \delta \phi_{\text{max}} \) induced by the SAW in the MZI arms. Figure 2(b) displays horizontal cross-sections of Fig. 1(a) for different \( V_{rf} \)’s. As expected from Eq. 1, the transmission for small \( V_{rf} \) (1.03 V) is dominated by oscillations at twice the SAW frequency (corresponding to a repetition period of \( T_{SAW}/2 = 0.96 \, ns \)). A weak component at \( f_{SAW} \), which accounts for the variation of the transmitted amplitude in successive cycles, is attributed to a non-vanishing \( \delta \phi_s \) induced by slight asymmetries between the WG arms. With increasing \( V_{rf} \), the average transmission reduces and the modulation shows strong components at higher harmonics of \( f_{SAW} \). In particular, a strong 4th harmonic component appears for \( V_{rf} = 3.7 \, V \) in Fig. 2(b). The reduced amplitude of the harmonics above 1.5 GHz is partially accounted for by the time resolution of the detection setup of approx. 0.6 ns. From a comparison of the average transmission levels with the predictions of Eq. 1 we have determined a ratio \( \delta \phi_{\text{max}}/V_{rf} = 0.67 \, \text{rad}/\text{V} \). The efficient modulation at the SAW frequency of a MZIs with \( \delta \phi_s \approx \pi/2 \) has been reported in Ref. [17]: the results in Fig. 2 indicate that quasi-symmetric structures (i.e., with \( \delta \phi_s \approx 0 \)) can also be used for the generation of higher-order harmonics of the SAW frequency.
3. Acousto-optical multiple interference devices (AOMIDs)

An important functionality for integrated optics is the ability to continuously control the intensity of a light beam propagating through a WG as well as to switch the transmission on and off for an arbitrary time interval. Although the average transmission of the simple MZI of Fig. 1(b) reduces under a SAW, it never decreases below approx. 25%. In order to realize efficient switches, we have extended the acoustic MZI concept to include $N_P > 2$ interferometer arms connected in parallel\(^1\). Configurations for acousto-optic multiple interference devices (AOMID) with $N_P = 2, 4$ and $8$ are illustrated in Figs. 3(b)-(d), respectively. As in the previous section, we will assume that the WG arms are equal and displaced along the SAW path so as to experience SAW phases differing by a multiple of $2\pi/N_P$ with respect to each other. Under these assumptions, the transmission $T$ becomes

$$T^{(N_P)}(t) = \left| \frac{1}{N_P} \sum_{p=0}^{N_P-1} e^{i(\delta \phi_{\text{max}} \sin [2\pi(f_{\text{SAW}}t + p/N_P)])} \right|^2 \overset{N_P \to \infty}{=} J_0^2(\delta \phi_{\text{max}}).$$

For a large $N_P$, the transmission becomes time independent and given in the limiting case $N_P \to \infty$ by the square of the 0\(^{th}\) order Bessel function $J_0(\delta \phi_{\text{max}})$, which vanishes for $\delta \phi_{\text{max}} \approx 2.40$ rad. Figure 3(a) compares the time dependence of the transmitted intensity calculated from Eq. 2 for AOMIDs with different number of arms. By an appropriate choice of $\delta \phi_{\text{max}}$ (which is close to 2.4 rad for $N_P > 4$), the transmission becomes strongly suppressed when the SAW is turned on, thus illustrating the operation as a switch for arbitrarily long on/off times.

AOMIDs with different numbers of arms have been fabricated using the process described in Sec. 2. Figure 4(b) displays an optical micrograph of a device containing AOMIDs with 5 and 6 arms, which are pumped by the same IDT. In these structures, the single-mode WGs were defined by etching half way through the surface GaAs layers (etch depth of approx. 150 nm), as illustrated for the 6-fold AOMID in Fig. 4(a). The shallow etch reduces acoustic reflections and ensures that the acoustic intensity remains constant for all WGs. To address this point, the distribution of the acoustic field in the structure was measured using the microscopic interferometer displayed in Fig. 4(c). Figure 4(d) compares profiles for the acoustic surface displacement $|u_z|$ recorded along the SAW path across the two AOMIDs with the simultaneously measured optical reflection $R_0$. The high values for $|u_z|$ around the AOMIDs are an artifact of the measurements arising from the non-planar surface structure, which reduces the optical

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\(^1\) Similar functionalities can be achieved by connecting several MZIs in series[14].
Figure 4. (a) Schematic diagram and (b) optical micrograph of AOMID with $N_P = 5$ and 6 arms (the individual arms are not resolved). (c) Microscopic interferometer and (d) spatial profiles of the vertical displacement field $|u_z|$ and optical reflection $R_0$, used to determine the position of the AOMIDs.

reflection $R_0$. Outside the AOMID areas, however, $|u_z|$ remains approx. constant even after traversing a total of 11 WGs, thus showing negligible acoustic reflections at the AOMIDs. The low acoustic reflection levels are attributed to the small ratio between the etch depth and the acoustic wavelength. We note that acoustic reflections are present in the sample, as evidenced by the oscillations in $|u_z|$ with spatial period $\lambda_{SAW}/2$. These reflections, however, do not originate in the AOMIDs but probably at a second IDT placed to the right of Fig. 4(b) (not shown in the diagram).

Figure 5(a) displays a schematic diagram of an on/off optical switch based on a six-fold AOMID, which uses multimode interference couplers (MMI) to connect the interferometer arms to the input and output WGs. Time-resolved transmission traces for this device recorded for different rf-voltages applied to the IDT are displayed in Figure 5(b). In agreement with Fig. 3, the average transmission reduces with $V_{rf}$ and reaches a minimum of approx. 5% ($\approx 13$ dB) for $V_{rf} = 4V$, thus demonstrating the operation as a switch with arbitrarily long on/off times. Note, however, that the residual transmission in the off (i.e., light-blocking) state is significantly higher than the values of much less than 1% expected for devices with $N_P > 4$ [see Fig. 3(a)]. The high residual transmission in the off state has been traced back to imperfections during fabrication, which introduces differences in the light coupling efficiency and the optical path length ($\delta\ell$) for the different arms[17]. In fact, the measured residual transmission in the off state can be accounted for by assuming an effective difference in lengths of the interferometer arms of only 40 nm[18], which are comparable to the tolerances of our optical fabrication process. The asymmetries also account for the high intensity of the components of the transmission at the first (observed for $1.2 < V_{rf} < 2.9$ V) and second harmonics (for $2.9$ V < $V_{rf}$) of the SAW frequency. The transmission of a perfectly symmetric device with a number $N_P$ of arms remains
Figure 5. (a) Six-fold AOMID with multimode interference coupler (MMI) and (b) optical transmission for different rf-voltages $V_{rf}$ applied to the IDT.

invariant when the SAW phase changes by $2\pi/N_P$ [cf. Figs. 5(a) and 3(a)] and should, therefore, only contain harmonics of $N_P f_{SAW}$. Considerably higher switching contrasts are then expected from improvements in the fabrication tolerances.

4. Conclusion

In conclusion, we have demonstrated a new concept for acousto-optical interference devices, which are waveguide based and compatible with integrated optics. We have shown that efficient light modulators, harmonic generators, and attenuators can be realized by modulating Mach-Zehnder interferometers with several arms using a SAW.

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