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2×2 Mach–Zehnder interferometric switch based on hetero-\textit{n-i-p-i} quantum wells


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A 2×2 Mach–Zehnder interferometric switch has been developed employing 3 dB multimode interference (MMI) couplers and laterally contacted hetero-\textit{n-i-p-i} quantum wells as the active material providing refractive index changes. Switching over a 4π range between the cross state and the bar state with an on/off ratio of 17:1 has been observed. A record voltage-length product for switching is observed of less than 1 V mm. By exploiting the quadratic nature of the quantum confined Stark effect, a differential switching voltage as low as 0.2 V mm is observed in the push–pull configuration. © 1995 American Institute of Physics.

One of the critical components in integrated communication networks are photonic waveguide switches for switching and routing applications. For this purpose, Mach–Zehnder interferometer switches have been reported in the literature with voltage length products down to 1.9 V mm. It is the objective of this letter to reduce this switching voltage product even further by exploiting the advantages of a hetero-\textit{n-i-p-i} quantum well structure for providing refractive index changes in the arms of a Mach–Zehnder interferometer switch.

A schematic of a hetero-\textit{n-i-p-i} structure is shown in Fig. 1. The intrinsic layers of the hetero-\textit{n-i-p-i} structure contain a 10 period GaAs/AlAs multiple quantum well providing the required refractive index change at 850 nm due to the quantum confined Stark effect. A 2 μm wide waveguide has been selectively etched in the 0.5 μm thick AlGaAs cladding layer. The voltage is applied to the \textit{n}- and \textit{p}-doped layers using selective lateral contacts, which are evaporated on the side edges of a 16 μm wide mesa which is also shown in Fig. 1. Ideally, the \textit{n}-type Ge/Ni/Au Ohmic contact only establishes contact with the \textit{n}-doped layers and the \textit{p}-type Zn/Au metal contacts the \textit{p}-doped layers. A lateral voltage applied between both contacts results in an applied electric field along the growth direction of the quantum wells.

One of the advantages of a hetero-\textit{n-i-p-i} structure is the possibility for independent optimization of the operating voltage and the magnitude of the refractive index change. The operating voltage can be reduced since the thickness of each of the intrinsic regions can easily be as thin as 1000 Å. The achievable magnitude of the electrorefractive effect can be optimized by increasing the number of \textit{n-i-p-i} periods and thereby the number of active quantum wells inside the waveguide core.

An important aspect of the hetero-\textit{n-i-p-i} quantum well material is the reduced amount of free-carrier absorption compared to a conventional \textit{p-i-n} structure. In a switching network, the total length of the switches including the connecting waveguides is easily a few centimeters, leading to very large free-carrier absorption losses when the waveguide mode overlaps with doped layers. A \textit{p-i-n} structure with the same intrinsic layer thickness as our hetero-\textit{n-i-p-i} (1000 Å) and doping levels of 2.8×10^{17}/cm^3 still suffers from a 20 dB/cm absorption loss. In our hetero-\textit{n-i-p-i} structure, the doping atoms are confined within doped layers of 300 Å thickness with a doping level of 2.8×10^{17}/cm^3. The overlap of the waveguide mode with the conducting parts of the doped layers has been calculated to be ~3% for each doped layer in our hetero-\textit{n-i-p-i} structure, leading to 6.5 dB/cm free-carrier absorption loss for a hetero-\textit{n-i-p-i} with only two doped layers. Experimentally, a waveguide loss of 6.4 dB/cm was measured which can be further reduced by a factor of two by further reducing the width of the doped layers.

The basic layout of the switch is shown in Fig. 2. The incoming light is equally distributed into the two arms of the interferometer by the first 2×2 multimode interference push–pull configuration. The voltage applied between both contacts results in an applied electric field along the growth direction of the quantum wells.

![Diagram](image-url)

**FIG. 1.** (a) Schematic cross section of the hetero-\textit{n-i-p-i} modulator showing the selective lateral contacts to the \textit{n}- and \textit{p}-doped layers. (b) Schematic of the hetero-\textit{n-i-p-i} layer structure in which GaAs/AlAs quantum wells are inserted into the intrinsic regions for providing electrorefraction.

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FIG. 2. Schematic of the Mach–Zehnder interferometric switch with 3 dB multimode interference (MMI) couplers and electrorefractive tuning sections using laterally contacted hetero-n-i-p-i quantum wells.

(MMI) coupler. The second MMI coupler recombines the light into a single output waveguide. If no voltage is applied to the tuning section, the switch is in the cross state. The MMI couplers operate in restricted paired interference mode by accurate positioning of the input waveguides. This allows three times shorter couplers for the same MMI width. Two different couplers have been used, measuring 9.6×277 and 13.2×504 μm², respectively.

Both arms of the Mach–Zehnder interferometer (MZI) have electrodes on either side of the second etched mesa which contains the doped layers (see Fig. 1). The electrode lengths are 400, 600, and 800 μm, which, in combination with the two types of MMI couplers yield compact switches with a total device length of 1.4–2.2 mm. An advantage of the hetero-n-i-p-i material is that electrical isolation between the two arms of the MZI is not necessary since the sheet resistance of the very thin conducting layers is high enough for establishing electrical isolation.

We have processed eight different MZIs with different contact lengths and MMI sections. The switching behavior of all switches could be scaled according to the V²L product required for switching from the cross state to the bar state in which L is the length of the contact region to the hetero-n-i-p-i quantum wells. Scaling with the internal electric field E² is expected due to the quadratic nature of the quantum confined Stark effect. We observed surprisingly good scaling with the externally applied V² although this is not expected due to built-in fields and depletion effects.

The switching behavior of a switch with 600 μm contact length is shown in Fig. 3 for four different operating wavelengths. It can be seen that the switch can be operated over four half periods from the cross state to the bar state at 852 nm. The operating range reduces to two half periods further away from the band gap at 864 nm. It can be seen that a maximum on/off switching ratio of 16:1 (852 nm), 17:1 (855 nm) and 10:1 (864 nm) has been achieved for our MZI switch. The absorption loss due to the quantum well interband absorption at zero bias varies between 0.06 and 12 dB as shown in Table I. Here it should be emphasized that this excess absorption loss is measured in a device cleaved to a total length of 7 mm in which the major part of the excess absorption loss occurs in the passive waveguides. Finally it can be seen from Fig. 3 that the average transmission decreases for increasing voltage due to electroabsorption, especially for the shorter operating wavelengths.

The figures of merit reported above have all been measured by applying a bias voltage to only one arm of the Mach–Zehnder interferometer and keeping the contact to the second arm floating. We have observed even more efficient switching by applying a small voltage difference between both tuning sections in the presence of a larger bias voltage applied to both tuning sections of the MZI. Such an equal bias applied to both arms of the MZI does not result in switching since it changes the index of refraction in both tuning sections by exactly the same amount. However, when, e.g., a bias voltage of 1.8 V is applied to both arms, complete switching is achieved with a 0.5 V differential voltage between both arms, corresponding to a voltage-length product.
of only 0.4 V mm at 859 nm. This very low differential voltage-length product again exploits the $V^2$ dependence of the quantum confined Stark effect. In addition, it allows an electronic driver circuit in the push–pull configuration where switching is already obtained at $\Delta V_1L = -\Delta V_2L = 0.2$ V mm. This voltage-length product provides nearly an order of magnitude improvement with respect to previously published results.

In conclusion, we have fabricated a Mach–Zehnder interferometric switch with tuning sections employing hetero-$n-i-p-i$ quantum wells as electrorefractive material. Our most compact MZIs have a total length of 1.4 mm. This is important for applications in switching matrices where many switches have to be integrated on a single chip. We observed switching over four complete half periods with on/off ratio’s up to 17:1 and a voltage length product below 1 V mm. In a biased push–pull configuration, switching was achieved at 0.2 V mm. A drawback of the design is the high sheet resistance which will impair frequency response. This work was supported by the Dutch Ministry of Economic Affairs through the IOP Electro-Optics Program.