# Optical switching based on high-speed phased array optical beam steering

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We present a high-speed optical switching scheme based on phased array optical beam steering, and analyze the trade-off between the switch power efficiency, signal-to-noise-ratio, number of output channels, and switching speed. For the proof of concept, a two-channel optical switch has been fabricated, using a high-speed GaAs/AlGaAs multiple quantum well phase modulator. We demonstrate a beam deflection angle of 100 mrad at the fastest ever reported speed of 18 GHz, consuming 1.8 mW. A signal-to-noise ratio of 8 dB is measured at each output channel. The relatively low signal-to-noise ratio can be further improved by increasing the number of phased arrays. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2831005]

Optical beam steering devices are becoming especially important because of their potential applications in optical interconnects, optical switches, and data conversion systems. A variety of methods have been reported to achieve optical beam steering by means of electromechanical and electrooptical effects. Although electromechanical beam-steering methods[1–4] provide a low-loss, high-angular resolution beam deflection, they are usually slow, power hungry, and bulky. Electrooptical beam steering schemes provide a motionless way to deflect the optical beam, thus having the advantages of fast response times, small device sizes, and long device lifetimes. The majority of electrooptical beam steering devices that have been demonstrated employ phase-arrayed waveguides,[5–8] or electrically tunable diffraction gratings.[9,10] However, the response time of most of the reported beam deflectors is too large for realizing an optical switch for telecommunication and internet applications.

In this work we present a high-speed optical switching scheme based on phased array optical beam steering and demonstrate a proof-of-concept two-channel switch prototype, using a high-speed GaAs/AlGaAs multiple quantum well phase modulator, performing 100 mrad deflection angle at the fastest ever reported, measurement instrument-limited deflection speed of 18 GHz and power consumption of 1.8 mW.

The schematic diagram of the proposed optical switch is shown in Fig. 1. The input optical beam is distributed among $N_i$ arrayed waveguides. An array of voltage-controlled phase modulators is integrated in the waveguide arrays. The phase modulators have a linearly varying length along the arrayed waveguides to induce a linear phase modulation along the waveguides, in response to $V_c$, the control electrical signal. Optical beam from $N_i$ arrayed waveguides enter a free propagation region, where they interfere and form a spot on an effective image plane. The position of this spot is proportional to $\Delta\phi$, the phase difference between the adjacent waveguides. In other words, the optical beam is deflected at an angle determined by the phase modulating voltage. If the dimensions of the output waveguides are set to be as large as the width of the resulting spot, the control electrical signal would determine the output waveguide to which the optical beam couples.

We use Fraunhofer diffraction theory to predict the resulting optical pattern on a far field image plane ($\Delta^2 \ll \lambda L$), where $\lambda$ is the wavelength, $\Delta$ is the waveguide spacing, and $L$ is the length of the free propagation region. The predicted optical pattern is a periodic pulse function with a sinc envelope. The main pulse, containing more than 85% of the total power, has a width of $2L\lambda/N_i\Delta$ and a deflection angle of $(\Delta\phi/2\pi)(\lambda/\Delta)$.

The number of arrayed waveguides, $N_i$, determines the width of the optical peak on the image plane and the deflection angular resolution, consequently. It also determines the number of resolvable output channels in an optical switch employing the discussed beam deflector. Switch power efficiency, defined as the ratio of the power at the selected output channel to the input power, is calculated using the optical intensity on the image plane associated with the selected channel. The trade-off between the power efficiency and the number of output channels (covering the whole deflection range), $N_o$, is shown in Fig. 2(a). Increasing the number of arrayed waveguides reduces the width of the resulting optical peak and increases the power efficiency.

Another important performance parameter is the signal-to-noise ratio (SNR) at each output channel. Since the deflection technique is an interferometric method, it is possible to couple a considerable amount of power from interference side lobes to undesirable output channels. This effect can also be mitigated by increasing the number of arrayed waveguides, $N_i$, [Fig. 2(b)] to increase SNR.

The particular benefit of the optical switch using the proposed phased array optical beam steering is the extremely

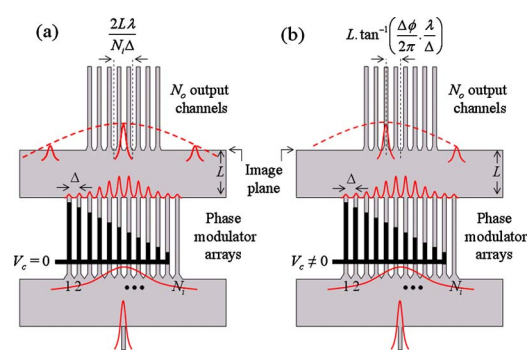


FIG. 1. (Color online) Schematic of the optical switch and its operation at (a) zero control voltage ($V_c=0$) and (b) non-zero control voltage ($V_c \neq 0$).

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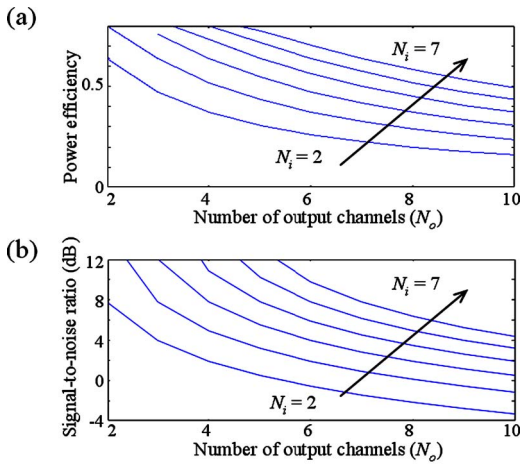


FIG. 2. (Color online) (a) Switch power efficiency and (b) switch signal-to-noise ratio as functions of the number of arrayed waveguides in an optical switch based on phased array beam steering.

high switching speeds afforded by the high bandwidth of optical modulators. The drawback of increasing the number of arrayed waveguides for the purpose of improving power efficiency and SNR is the bandwidth limitations of a large number of parallel phase modulators. Therefore, depending on the employed phase modulation scheme and the subsequent electrical signal distribution technique, there would be a trade-off between the switch speed and the switch power efficiency/SNR.

For a proof of concept, a two-channel optical switch based on the phased array optical beam steering was fabricated on a GaAs substrate. It consists of two arrayed waveguides connected to a free propagation region. The two arrayed waveguides are a part of a Mach-Zehnder interferometer [Fig. 3(a)]. A phase modulator is integrated in one branch of the Mach-Zehnder interferometer to vary the phase of the optical beam according to the control electrical signal $V_c$. Integrating two photodetectors inside the output waveguide channels enables measurement of the spatial distribution of optical power. Using the two-dimensional beam propagation simulation package BEAMPROP, we modeled the optical beam steering as a function of the modulator phase

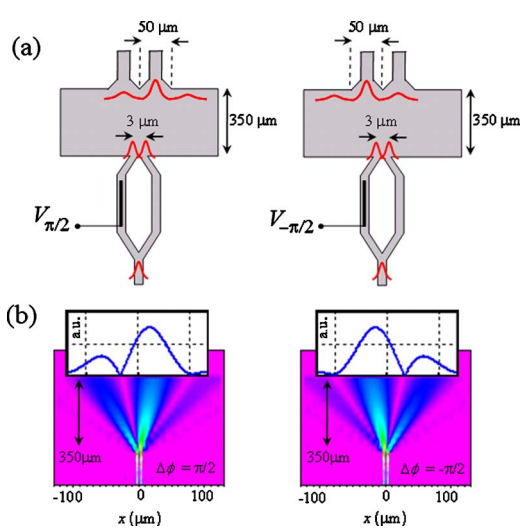


FIG. 3. (Color online) (a) Schematic of the fabricated two-channel optical switch. (b) Optical intensity on the image plane at an induced phase shift of $\pi/2$ and $-\pi/2$.

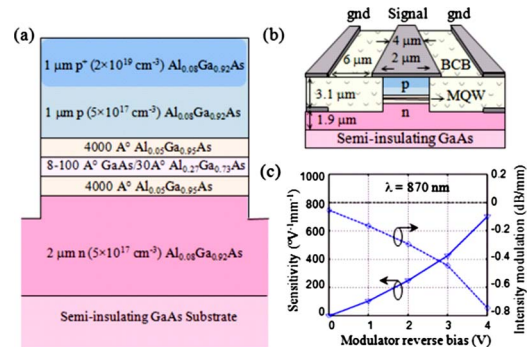


FIG. 4. (Color online) (a) Phase modulator *p-i-n* layers. (b) Schematic of the traveling wave phase modulator. (c) Measured phase modulation characteristics.

shift provided by the control electrical signal. Simulation results, illustrated in Fig. 3(b), show ±50 mrad deflection angle of the optical beam within an induced phase shift of $\pm\pi/2$.

Phase modulation arises from the quantum-confined Stark effect, in which an applied perpendicular electric field induces a shift in the absorption spectrum, and an accompanying shift in the refractive index of a multiple quantum well structure.[11] In this work, the multiple quantum well layers are a part of the intrinsic region of a reverse-biased *p-i-n* diode inside the optical waveguide [Fig. 4(a)]. The phase modulating electric signal propagates on a coplanar electrical waveguide (CPW) along the optical waveguide [Fig. 4(b)], to provide the electric field across the multiple quantum well layers in combination with the substrate bias. Traveling wave phase modulating electrical signal, velocity matched with the optical wave, allows a long modulation path while maintaining a small junction area.[12] Therefore, a high modulation bandwidth and efficiency is achieved simultaneously. The introduced phase shift in the optical mode is given by

$$\Delta\phi = \chi V_c L_m \frac{1 - e^{-\alpha L_m}}{\alpha L_m} e^{(-t/T_{\text{settling}})}, \tag{1}$$

where $\chi$ is the phase modulation efficiency in $^\circ\text{V}^{-1}\,\text{mm}^{-1}$, $V_c$ is the modulating electric voltage, $L_m$ is the length of modulator, $\alpha$ is the microwave attenuation, and the electric field settling time $T_{\text{settling}}$ is given by[12]

$$T_{\text{settling}} = 2.2\frac{d_m}{V} + 2\pi\frac{\rho\varepsilon}{d_m} + 2\pi L_m \frac{V_0 - V_c}{V_o V_c}, \tag{2}$$

where $d_m$ is the depletion region depth, $V$ is the carrier average drift velocity across the depletion region, $\rho$ is the *p-i-n* diode contact resistivity, and $V_o$ and $V_c$ are the velocities of the optical wave and the microwave, respectively.

At 870 nm, a phase modulation efficiency of 270 $^\circ\text{V}^{-1}\,\text{mm}^{-1}$, and an optical loss of less than 0.28 dB $\text{V}^{-1}\,\text{mm}^{-1}$ is measured for a substrate bias of 2.1 V. Using a 1.5 mm active region phase modulator, we measured $\pm\pi$ phase shift over a control electrical signal range of ±450 mV.

By calculating the CPW propagation constant from the scattering parameter measurements as a function of frequency, an electric field settling time of 2.1 ps and an electrical attenuation of less than 0.12 dB/mm are estimated for the traveling wave phase modulator. Therefore, the expected

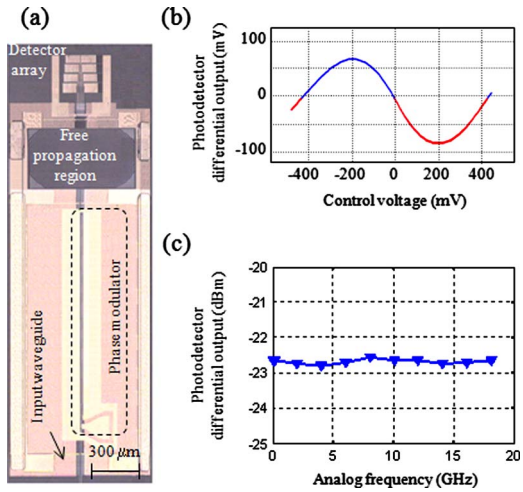


FIG. 5. (Color online) (a) Die micrograph of the fabricated switch. (b) Differential voltage between two output channels as a function of the control electrical voltage. (c) Frequency response of the switch output.

beam deflection speed is more than 50 GHz, where the CPW electrical attenuation is the primary speed-limiting mechanism.

The two photodetectors, integrated in the output channels, comprise *p-i-n* diodes monolithically fabricated in the output waveguides. The generated photocurrent along the photodetector active region is a function of multiple quantum well reverse bias set by the substrate voltage. The combination of a 350 fF parasitic capacitance and a 12 Ω parasitic resistance implies a bandwidth of 45 GHz for the fabricated photodetectors with 3200 $\mu m^2$ active area. A bandwidth of 33 GHz is measured for the fabricated photodetector, indicating a sufficient bandwidth to track an optical beam deflection up to 33 GHz.

A die micrograph of the fabricated switch is shown in Fig. 5(a). The phase modulator is 1.5 mm long, the free propagation region is 350 $\mu$m long, and the photodetectors occupy an area of 3200 $\mu m^2$. An optical beam power of 8 mW from a Ti-sapphire laser operating at 870 nm is coupled into the input waveguide.

The measured differential voltage between the two output channels over the control voltage range of ±450 mV is shown in Fig. 5(b). It indicates a switching between two output channels (an optical beam deflection of ±50 mrad) by varying the electrical control voltage from −225 to +225 mV. The detected optical power of about 0.5 mW at the selected output channel results in a power efficiency of 6.25%. By taking into account the total estimated photodetector quantum efficiency and the waveguide coupling efficiency of 10.8%, a power efficiency of 67.5% is calculated for the fabricated switch. Moreover, the measured signal-to-noise ratio at each output channel is 8 dB. Figure 5(c) shows the frequency response of the switch differential output. The differential output did not drop more than 3 dB over 1–18 GHz frequency range. Therefore, a measurement instrument-limited speed of more than 18 GHz, projected to the estimated speed of 50 GHz, is demonstrated for the fabricated two-channel optical switch.

As a summary, we have presented an optical switching scheme based on phased array beam steering. Highly efficient switching at large angular resolution can be achieved by using a large number of phased array waveguides in the beam deflector. Based on the phase modulation technique, there will be a trade-off between the switch speed and the power efficiency. One major drawback of the discussed switching scheme is the inherent diffraction noise induced by the interferometric deflection technique, reducing the signal-to-noise ratio at the output channels.

We have fabricated a two-channel optical switch on a GaAs substrate and demonstrated a 100 mrad deflection angle, consuming 1.8 mW. High-speed beam steering is achieved through the wideband phase modulation characteristics of the employed traveling wave phase modulator based on quantum-confined Stark effect. An instrument-limited beam steering speed of 18 GHz, projected to an estimated beam steering speed of more than 50 GHz, was measured. This is the fastest optical beam deflection ever reported.

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