



## Ultrahigh-speed, Broad-band, Integrated-Optic Mode Converter for 40 Gb/s Applications

Jeffrey Bull, Hiroshi Kato and Alan Guest  
JGKB Photonics Inc.  
Suite 221 - 4664 Lougheed Hwy.  
Burnaby, BC V5C 5T5  
Canada  
info@versawave.com

Nicolas Jaeger  
University of British Columbia  
2356 Main Mall  
Vancouver, BC V6T 1Z4  
Canada  
nickj@ece.ubc.ca

### ABSTRACT

An ultrahigh-speed, broad-band, integrated-optic mode converter is under development. It is intended for use in the next generation 40 Gb/s fiber-optic transmission systems. It has several key competitive features for its targeted application including low drive voltage, low chirp, broad-band optical response and wide electro-optic bandwidth. Currently the mode converters are fabricated in AlGaAs/GaAs but they could be fabricated in InP as well. Comparisons with other modulator types indicate that the mode converter is a competitive technology for 40 Gb/s applications.

## INTRODUCTION:

The recent explosive growth of data traffic has stimulated the demand for high capacity information networks. In order to further upgrade the overall capacity of optical, WDM transmission networks, the capacity per channel must be increased. The availability of high-speed optical modulators is key to achieving 40 Gb/s per channel.

As speed has increased in modern optical communication systems the direct modulation of lasers has become impractical so that currently in ultrahigh-speed long haul applications, external modulators are used. The first of these modulators to gain wide spread acceptance was the integrated-optic version of the Mach-Zehnder interferometer fabricated in the electro-optic material lithium niobate.

In this paper we discuss the integrated-optic mode converter [1,2] that is under development at JGKB Photonics Inc. and put it in perspective relative to the two most ubiquitous modulator types, the integrated-optic Mach-Zehnder and the electro-absorption modulator, in terms of key performance parameters.

## ISSUES FOR 40 GB/S TRANSMISSION:

A rule of thumb that is generally accepted in the trade regarding the effects of chromatic dispersion and polarization mode dispersion is that they increase at the square of the bit rate [3] for a fixed span. Therefore, in making the next jump in speed, from roughly 10 Gb/s to 40 Gb/s, we can expect a 16 fold increase in signal degradation due to these effects for a given transmission length. Since chirp is a principal source of line width broadening in an optical pulse, a brief discussion of chirp and chromatic dispersion. Also, since polarization mode dispersion is a deployment issue for 40 Gb/s systems, it will be touched on here as well.

**Chirp** - A chirped optical pulse is one in which the carrier frequency changes in time. For external modulators, chirp is often expressed as a unitless parameter,  $\alpha$  [4]:

$$\alpha = \frac{2I \frac{d\phi}{dt}}{\frac{dI}{dt}}$$

where  $I$  is the instantaneous optical power,  $t$  is time, and  $\phi$  is the instantaneous phase. For positive values of  $\alpha$ , the leading edge of the pulse is blue-shifted while the trailing edge is red-shifted (opposite shifts are generated when  $\alpha$  is negative). In fibers having anomalous dispersion, the blue-shifted light travels faster than the red-shifted light [5]. The result is that positive values of chirp will lead to pulse broadening, while some degree of pulse compression occurs with negative chirp. Since directly modulated lasers produce large positive chirp, external modulators have been used as a low chirp alternative, allowing improvements in achievable bit rates and distance [6].

**Chromatic Dispersion** - Chromatic dispersion in an optical fiber causes the different optical wavelengths found within an optical pulse to travel with different speeds. Its effects can be corrected through the introduction of a dispersive element of opposite sign (dispersion can be positive or negative). Fortunately, such an element can be relatively simple, inexpensive and passive once set to the right correction. Chromatic dispersion is generally required on a per channel basis in WDM systems, as each wavelength sees a slightly different chromatic dispersion characteristic in the fiber.

**Polarization Mode Dispersion** - Polarization mode dispersion (PMD) is the dispersion that results from birefringence in the optical fiber. The birefringence can arise from effects such as non-circularity of the core of the fiber or stresses induced in the fiber and is thus a dynamic effect, changing in time with temperature and movement of the fiber. While the effect of PMD is sufficiently small that 10 Gb/s systems do not need corrections, at 40 Gb/s it becomes a significant impairment that can limit the distance between repeaters. Therefore, achieving an optical link at 40 Gb/s of many hundreds of kilometers is challenging. Systems for compensating for PMD must be active and have been, to date, both complicated and expensive. Nevertheless, a rule of thumb financial formula for past line rate increases has been that, when a system with a four fold increase in bit rate costs less than 2.5 times the incumbent system, then the new system dominates.

## MODULATOR TECHNOLOGIES:

There are three modulator technologies for use in 40 Gb/s and above optical transmission systems that we will consider: the electro-absorption modulator, the integrated-optic Mach-Zehnder, and the integrated-optic mode converter. The first two of these have been used extensively to date and the third is currently under development. In the remainder of this paper we provide a description of each of these technologies and compare them in terms of principle performance issues.

**Electro-Absorption Modulator** - Two approaches to electro-absorption modulators exist. In the one the quantum confined Stark effect is used to shift the band edge within the modulator to lower energies and thereby increase the absorption of the device at the optical frequency being used. The second type uses the Franz-Keldysh effect to shift the band edge. Electro-absorption modulators are fabricated in compound semiconductors.

**Integrated-Optic Mach-Zehnder** - In its most common configuration, the integrated-optic Mach-Zehnder works by coupling the optical modes of two optical channel waveguides into a single output waveguide using a coupling horn that forms part of a combining optical Y-branch. The relative phases of the optical modes within the coupling horn of the output Y-branch determine which modes are excited in the output waveguide. If the waveguides are designed to support only the lowest order TE (transverse electric) or TM (transverse magnetic) mode, then the light will couple into the lowest order mode of the output waveguide or will be radiated into the substrate surrounding the waveguide. The relative phase in the combining Y-branch will control the proportion of light coupled into the output waveguide, or into the surrounding substrate, in a way that depends sinusoidally on the relative phase.

In order to control the relative phases of the two modes in the combining Y-branch the speed that the light travels in each of the two waveguides is controlled electro-optically by applying an electrical signal to sections of each of the waveguides, the phase control waveguide sections. The light is injected into each of the waveguides by using a bifurcating optical Y-branch at the input to the

Mach-Zehnder. This bifurcating Y-branch couples light from a single input waveguide equally into each of the two branches. Figure 1a shows an integrated-optic Mach-Zehnder with the optical modes in the combining Y-branch in phase and Figure 1b shows one with the optical modes 180° out of phase. The integrated-optic Mach-Zehnder can be fabricated in either compound semiconductors and in lithium niobate.

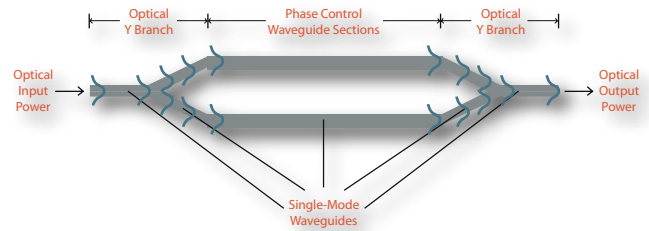


Figure 1a. An integrated-optic Mach-Zehnder with no phase shift between the modes at the output Y-branch.

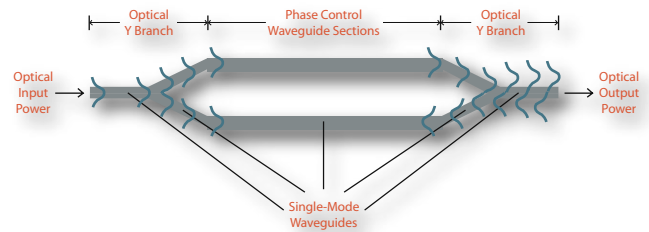


Figure 1b. An integrated-optic Mach-Zehnder with a 180° phase shift between the modes at the output Y-branch.

**Integrated-Optic Mode Converter** - The integrated-optic mode converter is in many ways similar to the integrated-optic Mach-Zehnder. It uses the interference between two modes to modulate the output light of a single mode waveguide between the waveguide's TE mode and its TM mode. As in the Mach-Zehnder, this is done electro-optically by the application of an electric signal to the waveguide. The main difference between the Mach-Zehnder and the mode converter is that this is all done in a single waveguide. Light is injected into the waveguide in one of the two modes, i.e., the TE or the TM mode. It then propagates through a section in the waveguide where the optical properties are affected by the application of an electric field. This section is designed so that the natural modes are hybrid modes with their electric fields oriented at 45° to those of the TE or TM modes. The input mode

then resolves itself into these hybrid modes and the applied electric field alters the speed of these hybrid modes so that the speed of one is increased by a small amount and the other is decreased by an equal amount. These hybrid modes are then mixed at the output of the device and the phase difference results in a change of the polarization state. The integrated-optic mode converter differs from a polarization rotator in that in the transitions between TE light and TM light the output passes through a continuum of elliptical polarization states, whereas in polarization rotators the light stays linearly polarized with the direction of polarization changing. Since the total output power stays constant, only the polarization state is changing, the integrated-optic mode converter needs an analyser at the output in order to obtain an amplitude modulated signal.

Figure 2a shows an integrated-optic mode converter with the optical modes in the waveguide remaining in phase and Figure 2b shows one with the optical modes 180° out of phase at the output. The integrated-optic mode converter is fabricated in compound semiconductors, specifically they are being fabricated in AlGaAs/GaAs.

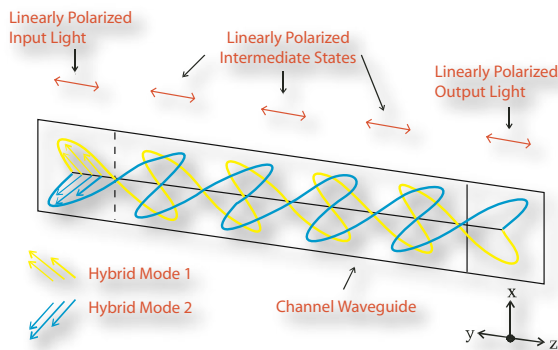


Figure 2a. An integrated-optic mode converter with no phase shift between the modes in the waveguide.

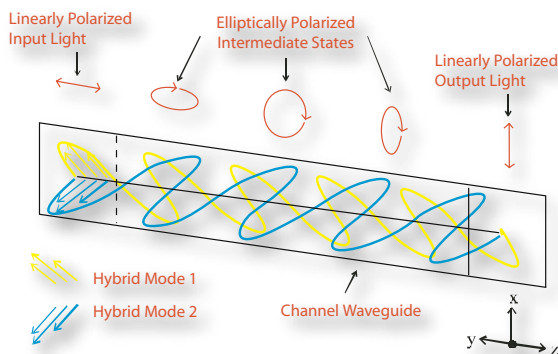


Figure 2b. An integrated-optic mode converter with a 180° phase shift between the modes at the output.

## COMPARISON OF MODULATOR TECHNOLOGIES:

There are numerous advantages for using GaAs-based technology. The first and foremost is the maturity of the technology and the manufacturing processes that have been developed over the past thirty years or so to make both electronic and optoelectronic devices. Specifically, the integrated-optic mode converter leverages technology refined in the last decade to make waveguide based laser diodes and photodiode structures. These include processes such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), which allow precise control of both the waveguide structure and refractive index contrast, automated dicing tools capable of creating high quality optical facets, and anti-reflection coatings that are robust and capable of handling high optical power densities.

There are a number of manufacturing advantages which compound semiconductors offer that are not available for lithium niobate. For instance, lithium niobate devices are made by the in-diffusion of dopants such as titanium into lithium niobate substrates to create waveguides, whereas in compound semiconductors waveguides are usually formed by etching ridges in epitaxial layers. The accuracy and control of layer thickness and waveguide width is much tighter for compound semiconductors using MBE or MOCVD processes. An additional cost element for lithium niobate is the preparation of optical facets on the ends of the waveguides, these must be sawn and polished as opposed to the cleaving techniques that can be used for compound semiconductors. Furthermore, major cost savings can also be achieved in GaAs, e.g., GaAs wafers are available in sizes up to 6" diameter whereas lithium niobate and InP are only available in 3" or 4" sizes. There are also cost considerations in the packaging of any optical device. For example, to meet the operating specifications over a wide range of temperatures requires the careful matching of the thermal expansion coefficients of all the materials in a product. GaAs is well matched to a variety of inexpensive and machineable materials such as Kovar™, alumina, Cu/W, and AlSiC.

The "interferometric" modulators, i.e., the integrated-optic Mach-Zehnder and mode converter, are optically broad-band in that a single device can be

used over for a wide range of optical frequencies, e.g., the C or L bands, or both. In contrast to this electro-absorption modulators are sensitive to wavelength [7]. On the other hand, electro-absorption modulators have the lowest drive voltages of the modulators being considered here. Commercially available electro-absorption modulators have drive voltages of about 3 V where as Mach-Zehnders have drive voltages in the 5 to 6 V range. The integrated-optic mode converters that are presented here have measured drive voltages in the 4 to 6 V range and have the potential to reduce the drive voltage to the 3 to 4 V range [1].

An important consideration for 40 Gb/s operation is the electro-optic (e-o) bandwidth. Commercially available electro-absorption modulators have e-o bandwidths of up to 36 GHz and integrated-optic Mach-Zehnders have e-o bandwidths of up to 33 GHz whereas mode converters are being designed to have e-o bandwidths of 40 GHz. Figure 3 shows a derived (using electrode loss and electrical signal velocity measurements) e-o  $S_{21}$  over a wide band of frequencies for an integrated-optic mode converter.

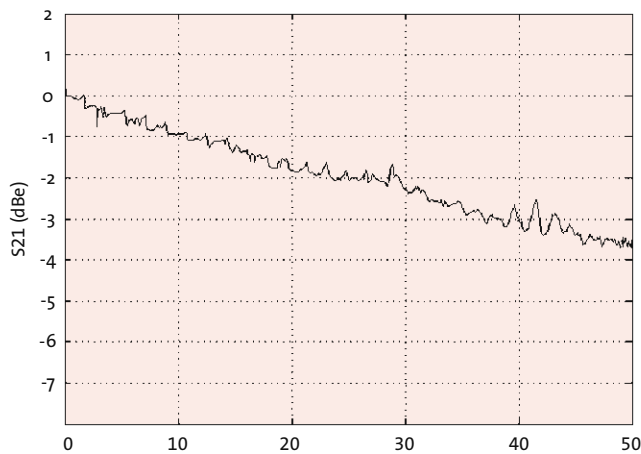


Figure 3. Electro-Optic  $S_{21}$  over frequency for an integrated-optic mode converter.

Another issue that is of interest to system integrators is package size. A comparison of package sizes shows that the electro-absorption modulators have the smallest packages. Of the other modulators, the heights and widths tend to be similar but the lengths vary considerably. Of the remaining modulators, the integrated-optic mode converter has the shortest package, from 2 to 2.5 inches long, and lithium niobate Mach-Zehnders

have the longest packages, at 3.5 to 4.5 inches long.

A modulator can introduce chirp if its effective optical path length changes as a function of time due to the modulation. Electro-absorption modulators produce intensity modulation by changing the absorption, or imaginary refractive index spectrum of a guided wave structure. Chirp is generally produced as a result due the accompanied change in the real part of the refractive index as predicted by the Kramers-Kronig relations [4]. Although chirp in an electro-absorption modulator can be controlled to some extent [6, 8], doing so is considerably more complex than in interferometer type modulators. Modulators based on the linear electro-optic effect, or Pockels effect, rely on retarding and advancing the phase of an optical path. In the case of a Mach-Zehnder, zero chirp can be obtained if each branch of the interferometer is equally and oppositely phase modulated (push-pull) so that the sum of each branch produces an intensity modulation without phase modulation. In practice, achieving zero chirp in a push-pull Mach-Zehnder also requires carefully balanced power splitters and combiners so that each arm of the interferometer contributes an equal amount of power to the output signal. The chirp of the integrated-optic mode converter is nominally zero. The reason for this can be understood by considering the electro-optic coefficients “seen” by an optical mode propagating along a [110] direction in (001) GaAs. Application of an electric field lying in the plane of the substrate, perpendicular to the propagation direction, results in equal and opposite phase changes for the two hybrid modes of the mode converter. At the termination of the mode converter, the superposition of the two hybrid modes obtained with an analyser produces an intensity modulation in response to the differential phase change of the hybrid modes. So long as equal powers from each hybrid mode pass through the analyser, the phase of the resulting light wave is not modulated and so can nominally produce zero chirp. The zero chirp condition holds even if the mode conversion efficiency is not 100 %, provided that the input polarizer is crossed with the analyser. For example, if the TE mode is launched, then the analyser should be set to pass the TM mode.

Figure 4 illustrates a comparison of all of the modulator types being considered. The comparison

of drive voltage, chirp and package size where proximity to the origin is desired.

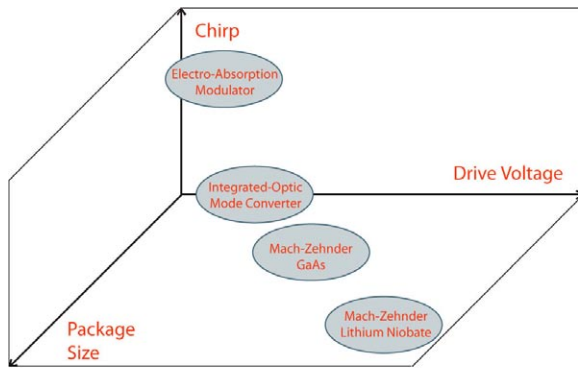


Figure 4. Modulator technology comparison

In many modulator technologies drive voltage and bandwidth are interrelated. A figure of merit for comparing modulators that takes this into consideration is the following [9]:

$$F = \frac{2R}{50 + R} \frac{f_o}{V_d} \lambda$$

where  $R$  is the modulator impedance,  $f_o$  is the e-o bandwidth,  $V_d$  is the drive voltage, and  $\lambda$  is the optical wavelength. Table 1 provides a survey of typical commercial modulator specifications.  $R$  has been taken to be 50 ohms to remove mismatch loss from the comparison since this loss is relatively comparable among the modulators.  $\lambda$  has also been

removed from the figure of merit since 1550 nm is common to all the modulators presented here. In cases where only low frequency  $V\pi$  is given, a factor of 1.3 has been used to convert low frequency  $V\pi$  to drive voltage.

lithium niobate, the top performers are the GaAs-based technologies and that the GaAs mode converters outperform the GaAs Mach-Zehnder.

#### SUMMARY AND CONCLUSION:

The deployment of 40 Gb/s systems is inevitable but this will be timed to cost improvements and technical solutions to limiting issues such as polarization mode dispersion. Modulator technology improvements embodied in the integrated-optic mode converter reduce system costs and the effects of dispersion. The advantages of using a GaAs-based technology as compared to lithium niobate or InP-based ones has been discussed. The comparison between the integrated-optic mode converter and the two most commonly used modulators, the electro-absorption modulator and the integrated-optic Mach-Zehnder, shows that the mode converter has superior performance compared to the electro-absorption modulator in terms of chirp, e-o bandwidth, and optical broad-band operation, and that they have superior performance relative to integrated-optic Mach-Zehnders in terms of drive voltage, e-o bandwidth, and package size.

Table 1. Figures of Merit for Several Commercial Interferometric Modulators.

Modulator Type	E-O Bandwidth (GHz)	Drive Voltage (V)	Figure of Merit
Lithium Niobate Mach-Zehnder (wide e-o bandwidth)	30	6	5
Lithium Niobate Mach-Zehnder (low drive voltage)	22	5.2	4.2
GaAs Mach-Zehnder	33	5.5	6
GaAs Mode Converter (wide e-o bandwidth)	40	6	6.7
GaAs Mode Converter (low drive voltage)	33	4	83

In Table 1 a comparison is made of the figures of merit for several commercially available interferometric modulators. Specifically, GaAs-based technologies are compared with lithium niobate technologies and integrated-optic Mach-Zehnders are compared to mode converters. It is clear from Table 1 that, despite the high electro-optic coefficient of lithium niobate, the top performers are the GaAs-based technologies and that the GaAs mode converters outperform the GaAs Mach-Zehnder.

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## About Versawave

Versawave provides modulation components for high-speed data and high bandwidth optical communication applications. Versawave's proprietary GaAs-based designs provide system manufacturers with cost effective solutions that offer design flexibility, small footprints and power efficiency. Used for either polarization or amplitude modulation applications, these designs are fully compatible with commercial foundries for chip manufacture and packaging. In addition, Versawave utilizes its advanced prototyping facility to design custom components and provide fabrication services to the optical networking industry. Versawave is a division of JGKB Photonics Inc., a privately held company based in Vancouver, British Columbia.

### **JGKB PHOTONICS INC.**

Suite 221  
4664 Lougheed Highway  
Burnaby, BC, V5C 5T5  
Canada

+1-604-221-5452 tel  
+1-604-221-5453 fax

info@versawave.com  
versawave.com