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ELECTRO-OPTIC MODULATORS FOR SPACE USING GALLIUM ARSENIDE

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I. INTRODUCTION

There is increasing interest in the use of optical methods for managing RF signals in space, with applications for both ground-to-satellite and inter-satellite communications readily envisaged. The potential weight-saving of optical fiber over metallic waveguide or coaxial channels is very significant; moreover, there are obvious advantages to be gained from the enormous data capacity of multiplexed fiber links.

In civil telecom and datacom, the impetus towards ever higher data-rates has driven the development of increasingly complex coherent optical modulation schemes capable of encoding multiple channels onto the same wavelength. These usually have a basis in phase-shift keying (PSK) but extended using quadrature phase-states (QPSK), dual orthogonal polarization states (DP-QPSK) and finally amplitude diversity (QAM). Further multiplication of the channel count is then possible using a comb of different wavelengths in wavelength multiplexed schemes.

This has justified significant developments in high-functionality Photonic Integrated Circuits (PICs) based on high bandwidth electro-optic modulators. The Mach-Zehnder Interferometer configuration is ubiquitous in such PICs due to its high speed, low chirp and well-defined non-linear properties. Its periodic, raised-cosine Light/Voltage characteristic is ideally suited for digital modulation, providing not only a pair of adjacent saturating *High* and *Low* amplitude levels but also a repeating set of *High* levels which alternate in optical phase. This phase-reversal property is the basis of PSK encoding using Mach Zehnder modulators (MZM).

Applications for space have much in common with the military and avionic applications which drove much of the early development of the gallium arsenide electro-optic modulator which is the subject of this [1],. Where these *aerospace* applications tend to differ from the digital telecom world is in frequently requiring analogue rather than digital modulation. This is due to the importance of RF-over-Fiber (RoF), for which the linearity and symmetry of the modulation characteristic is important. It is also vital that the component technology has excellent credentials of environmental and thermal stability, ruggedness, power-handling and longevity.

Fundamentally, the material system chosen for the modulator must have suitable electro-optical properties, which limits the choice to semiconductors, ferroelectric ceramics (usually lithium niobate) or electro-optic polymers. All of these may be persuaded to give excellent results (at least for a discrete modulator), but finally the choice for aerospace may be determined by environmental considerations.

II. PROPERTIES OF GAAS AND ALGAAS

Gallium arsenide (GaAs) has remained the material of choice for mm-wave electronic devices and integrated circuits for several decades. It has many desirable properties for RF devices which must survive and operate in harsh environments:

- Semi-insulating (SI) GaAs substrates are low-cost and have high-resistivity so can provide low-loss coplanar transmission-lines.
- The electron mobility is high - six times higher than in silicon and almost 60% higher than InP. This enables low optical loss and high RF bandwidth in opto-electronic and electronic devices.
- The bandgap is comparatively large at 1.424eV. This yields the required characteristics of environmental stability, including a good degree of radiation hardness [2]. Of the commonly-used semiconductors only diamond and GaN are higher. Silicon has a bandgap of 1.12eV.
- The related ternary $Al_xGa_{1-x}As$ is closely lattice-matched to GaAs throughout the range of aluminium-fraction *x*. Increasing *x* further increases the band-gap and reduces the refractive-index. This enables considerable freedom in designing AlGaAs/GaAs hetero-structures for the confinement of electrons (in quantum wells) and photons (in optical waveguides).

To fully exploit these properties, well qualified foundry processes have been developed over decades for the fabrication of GaAs discretes and monolithic microwave integrated circuits (MMICs). Thus, one further considerable benefit of GaAs for space applications is that it is already formally qualified to an appropriate standard for aerospace systems.

A. Environmental Stability

The useful property (for space) of *radiation hardness* is, of course, relative and is no substitute for effective shielding. A typical machined *kovar* package – thick and rigid enough to prevent distortion of the fiber-coupling arrangements – will enhance this, but will not in itself be sufficient. The radiation encountered in low-medium Earth orbit comprises primarily protons (85%), but also other ions, neutrons, electrons and gamma radiation. At sufficiently high energy all these can be damaging to any semiconductor component. In particular, a high-energy proton-flux can disrupt the GaAs crystal, reducing the desired conductivity due to doping and increasing optical absorption. Measurements are in-progress to assess the impact of this in packaged GaAs optical modulators. As noted above, GaAs is already widely used in space for electronic devices, so will already have been appraised for its radiation resistance.

GaAs modulators are also notable for their thermal stability. The long interferometer at the heart of any electro-optic modulator is very sensitive to any imbalance and the industry-standard lithium niobate (LN) modulators are notably prone to bias-point drift due to charge migration. This does not occur with GaAs.

Some electro-optic systems, such as those based on InGaAsP quantum wells, require to be maintained within a narrow temperature range to function correctly; these will typically incorporate a Peltier thermo-cooler within the package. Again, GaAs does not require this and will operate over a broad temperature range, though with some variation in $V\pi$, which is reduced by an increase in temperature.

For the same reason (the operating wavelength is remote from the band-edge), and unlike InGaAsP MQW devices, GaAs modulators are inherently tolerant of optical wavelength; they can even be designed for dual band operation encompassing both 'O' and 'C' bands centred on 1300nm and 1550nm respectively.

B. Optical Properties of the GaAs/AlGaAs Material System

$Al_xGa_{1-x}As$ has similar properties to GaAs up to x ~0.4 where the fundamental energy gap becomes indirect; higher aluminum fractions than this are rarely used. In addition to the basic properties listed above, the AlGaAs material system has optical properties which enable it to be used for photonic devices:

a) As a direct-gap semiconductor it can be used as a light emitter (LED or Laser) for wavelengths shorter than the fundamental band-edge (~870nm).
b) As a non-elemental III-V compound, the crystal is non-centrosymmetric. This provides a linear electro-optic (LEO) effect, which is a small change in refractive-index in response to an applied electric field. The LEO is all-important for modulators at longer wavelengths, with wavebands around 1300nm and 1550nm being of primary interest for fiber systems.
c) Close to (but longer than) the band-edge, electro-absorption and the associated quadratic electro-optic (QEO) effect dominate; however, these effects are weak in the important 1300nm and 1550nm bands.
d) For wavelengths longer than the band-edge (e.g. >1000nm) the intrinsic (undoped) absorption is very low meaning that low-loss optical waveguides can be made.
e) The optical refractive-index is high (~3.4) and is similar to the equivalent microwave parameter (~3.6)

In contrast to the above, silicon – an indirect-gap elemental semiconductor – does not emit light and exhibits no LEO effect. Modulators made in silicon must rely on the non-linear QEO and free-carrier sweep-out effects.

III. OPTICAL WAVEGUIDE MODULATORS

Optical waveguides based on an $Al_xGa_{1-x}As$ heterostructure layer-stack are grown by either Molecular Beam Epitaxy (MBE) or Metallo-Organic Vapour Phase Epitaxy (MOVPE) epitaxial methods. The GaAs/AlGaAs refractive-index contrast provides a basis for efficient waveguide design with light confined within a high refractive-index 'core' layer set between 'cladding' layers of higher x. Lateral confinement is provided by etching the surface to create rib (shallow etch) or ridge (deep etch) waveguides as illustrated in Fig. 1.

As with all semiconductors, the conductivity of the materials can be engineered by doping with impurities during growth. The n-type electrical back-plane contact is in-grown beneath the waveguide. The top-contact can also be grown as a p-type capping layer; however, there are advantages in using a metal-to-semiconductor Schottky evaporated contact instead. In either case the waveguide cross-section is in the nature of a diode. A vertical E-field due to reverse-biasing the diode is optimized to interact efficiently with the light using the electro-optic effect. Optimization consists in adjustments to the aluminum compositions, the layer thicknesses and the position of the doped back-plane relative to the surface. It attempts to achieve the best balance of optical mode-size (large is good) versus electro-optic efficiency and electrical capacitance, with tolerable optical losses due to free-carrier and metal-electrode contributions.

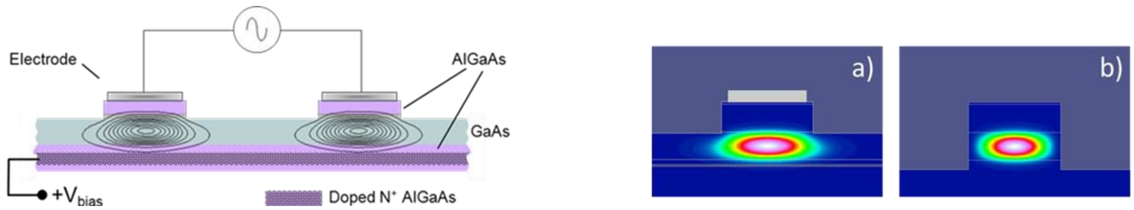

Fig. 1 *Left:* Section of the GaAs/AlGaAs Mach-Zehnder modulator. *Right:* fundamental optical mode contours for (a) shallow rib waveguide with electrode, and (b) deep ridge passive waveguide.

In addition to the LEO, there are carrier sweep-out and residual QEO effects. These are small, but it is generally arranged to ensure all contributions add constructively.

A. Waveguide Process Technology

Our GaAs modulator technology is built upon a commercial GaAs foundry pHEMT process which has demonstrated high yield under high volume conditions of up to 1000wspw [3]. The process works to a set of design rules which are standard in the industry. This translates into a robust process backed by high levels of manufacturability.

B. GaAs Traveling Wave Modulators

The Mach-Zehnder modulator (MZM) consists of an optical splitter feeding into the pair of electro-optic waveguide phase modulators shown in cross-section in Fig. 1. The bias and RF drive are set-up to operate in *series push-pull* [4]. The built-in back-to-back connection (via the n-type backplane) creates a series-chain so the effective capacitance is halved, while the RF drive-voltage is split equally, resulting in balanced, anti-phase contributions with no net phase modulation after recombination to cause *chirp* in the output signal.

Upon recombination, the differential phase-shift resulting from the electro-optic effects produces a raised-cosine output-intensity function characterized by the half-wave voltage V_{π}. This characteristic is desirable for a number of RoF applications. Bias to the mid (inflexion) point yields optimally linear intensity modulation with no even-order harmonics while bias to the minimum turning-point yields a near square-law characteristic for frequency-doubled or double-sideband suppressed carrier (DSSC) modulation. This native DSSC modulation can advantageously be further processed to create single-sideband (SSB) modulation by mixing the DSSC outputs from two identical modulators as shown in Fig. 2. Such SSB modulation is of considerable interest for RoF systems.

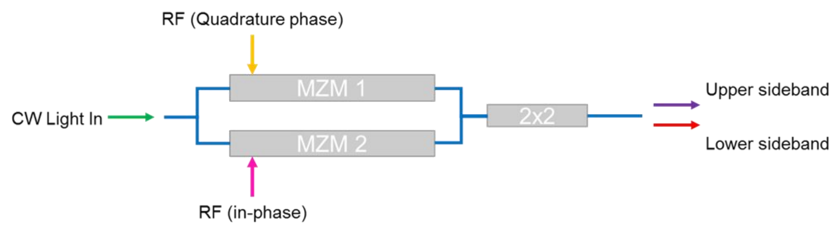

Fig. 2 Dual MZM configuration for the generation of single-sideband (SSB) modulation

Fig. 3. Illustrates the velocity-matched, travelling-wave MZM configuration used with GaAs/AlGaAs. This is a *capacitively loaded line* configuration based on segmented modulation electrodes within a larger scale CPS or CPW transmission-line.

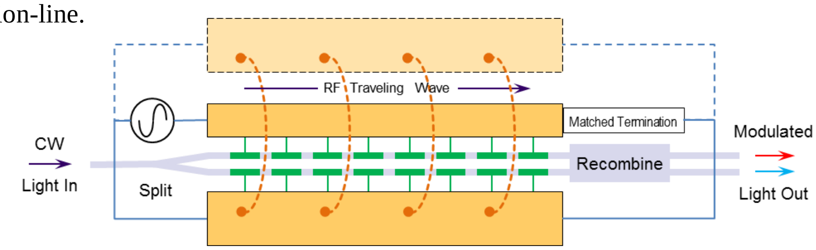

Fig. 3 Schematic of loaded line travelling wave modulator based on CPS or CPW (dotted) transmission-line.

The need for velocity-matching in electro-optic modulators originates from the weakness of electro-optic effects available in most materials; to achieve a desirably low V_{π} requires very long phase-modulator arms. V_{π}~3V is typically targeted, requiring up to 30mm between split and recombination in a GaAs device. Even relatively short (a few mm) modulators do not function as truly ‘lumped’ devices and require to be modelled as open-ended transmission-lines [5], [6].

The primary aim in traveling-wave design is to match the velocity of a forward-propagating RF voltage-wave launched at the input-end of the electrodes with the velocity of the optical modulation group which is being created through the electro-optic effect. Only if this is done perfectly can the modulation-depth accumulate monotonically along the entire length of the electrode. RF reflections are suppressed by proper termination of the transmission-line; a reflected counter-propagating RF wave only makes a significant net contribution at very low frequency (but adds ripple otherwise) producing a very uneven response.

The *capacitively loaded line* configuration, illustrated in Fig. 3 was first proposed and demonstrated in 1989 [1] [7] and has been generally adopted for traveling-wave devices of many kinds in semiconductor materials. This configuration is a slow-wave structure which is able to bring the RF wave into match with the light wave. As noted above for GaAs, (but generally true for semiconductors) the microwave and optical velocities in the material have similar values. However, while the *optical* field is fully embedded in the material the coplanar *RF* field is ~50% air-loaded and consequently runs much faster in the absence of the capacitive loading.

The modulation electrodes are divided into a periodic array of short segments isolated by passive spaces to ensure behaviour as reactive lumped elements and not as a competing, lossy transmission-line. The electrodes sample the line-voltage periodically via air-bridge connections. This versatile scheme allows a variety of waveguide designs to be incorporated into a velocity-matched device since the net capacitance per unit length of loading electrode is adjustable by means of the electrode *filling-factor* and/or waveguide width. The loaded characteristic impedance and RF velocity are both subject to the same slow-wave factor and in GaAs a good velocity-match generally coincides with impedance a little under 50Ω.

C. CPW Modulators

Although Fig. 3 illustrates both CPS and CPW options for the coplanar transmission-line, the CPW geometry is generally found to be preferable for bandwidths up to 40GHz. Above 40GHz the lower dispersion of symmetric CPS (two equal-width conductors) appears superior in isolation, but its fundamentally *balanced* operational mode is in conflict with the *unbalanced* nature of standard hermetic packaging arrangements where one RF rail is identified with the package metalwork. This makes it hard to realize the inherent quality of the chip in a real packaged device; with one rail shorted to ground at the input, the impedance is reduced locally, increasing the VSWR and exciting unwanted RF modes.

With CPW, the native RF mode is much more unbalanced in nature due to the very wide ground-plane total compared to the narrow signal-line. Conflict with the fully unbalanced package, though not zero, is greatly reduced. One complication with CPW is the need to strap the two ground-planes together, but this is readily accomplished by automated wire-bonding. The GaAs modulator illustrated Fig. 4 uses a CPW transmission-line with 300 electrode-segments on a 100µm pitch and with a 95% fill-factor. The bandwidth shown is typical for these devices at >30GHz, with the RF S11 <-10dB.

This MZM adopts the industry-standard OIF (*Optical Internetworking Forum*) layout, designed primarily for lithium niobate (LN) modulators. Lithium niobate waveguides are weakly confining and consequently cannot implement low-loss small-radius bends. This defines the standard *Fiber-in-Line* arrangement and large package size with RF access from the side. A GaAs modulator is typically much smaller than a LN modulator of similar characteristics and can use a smaller package footprint.

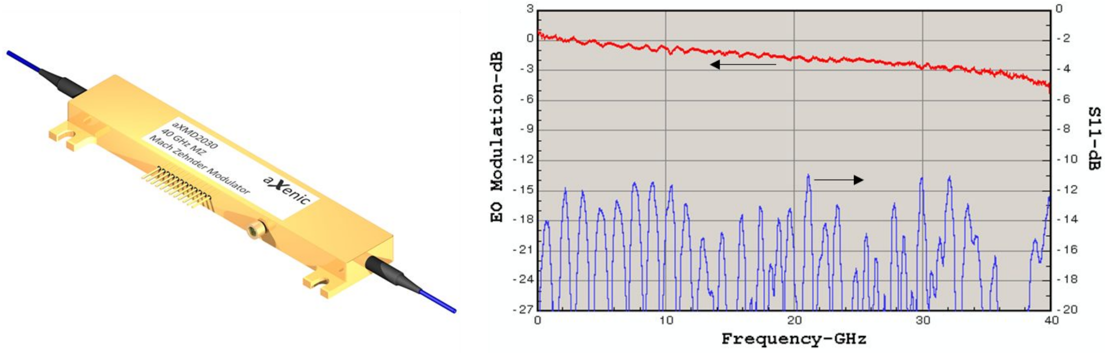

Fig. 4 35GHz, 3V GaAs MZ Modulator based on ground-strapped CPW coplanar system.

IV. RF INLINE CONFIGURATIONS

Low loss small-radius bends can be implemented using GaAs ridge waveguides [8]. For this reason, GaAs is well-suited to realizing modulator configurations of higher functionality in which more than one MZM is integrated onto a single chip. While pairs of two MZ channels – typically used for QPSK or SSB modulation – may still offer a balanced symmetrical configuration with RF access from each edge of the chip, this is not possible if more than two channels are wanted. Arrays of modulators are of interest for RF beamforming applications.

As seen in Fig. 4, a smooth high-bandwidth response is possible if the MZ channel is near the edge of the chip and the RF 90° bend is small and smooth. Inner channels (and the far-side channel if all are accessed from the same side) become increasingly compromised by long access runs; the RF bends can cause mode conversion and increasing loss at the more remote channels. For this reason, our recent designs all use a new *single-ended* configuration in which all RF access is from one end on the chip while all optical access is via the opposing facet. The advantages in terms of RF access are clear:

- All RF input runs are identical and can be short.
- RF input runs are straight so not prone to introduce RF asymmetries and extra modes.
- Any number of channels can be addressed in this way, allowing arrays of devices to be integrated in one package.

Fig. 5 illustrates this for a dual MZ (IQ or SSB) configuration. Single Sideband (SSB) generation requires a good balance between the two channels; the single-ended configuration is therefore potentially beneficial for this.

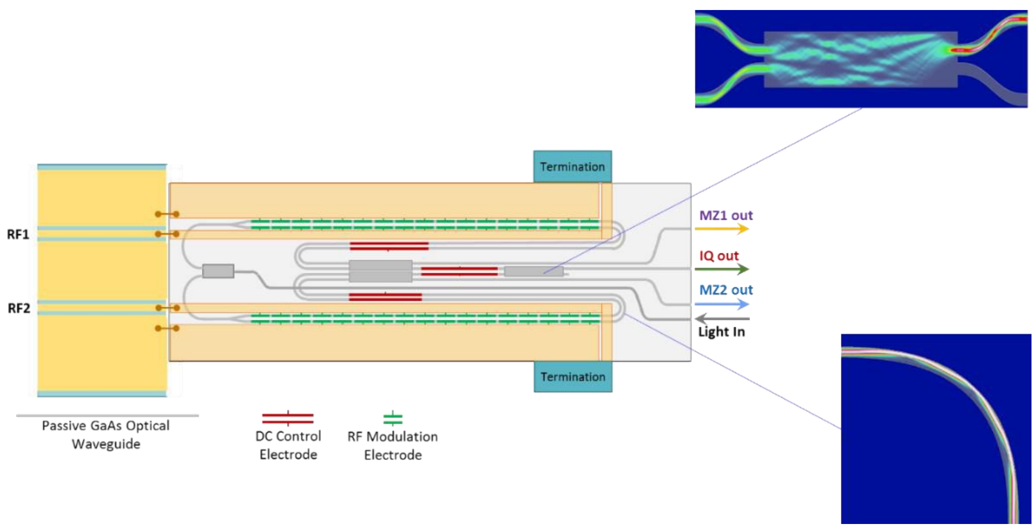

Fig. 5 Single-ended configuration of two MZM channels, for 1x2 array or IQM application. (also showing 2x2 MMI coupler and corner-bend simulations)

RF terminations are placed at the chip-edges to avoid impeding the optical-interface arrangements. Our prototype four-channel modulator array uses side termination for all channels, requiring extra coplanar tracking on the inner channels to implement terminal-runs to the chip edges. The RF termination is less critical than the RF launch because the capacitively loaded line itself acts to attenuate any high-frequency RF returning from the back-end of the device.

A. Optical Couplers and Bends

Multi-mode interference (MMI) principles are used to design various optical couplers, splitters and recombiners [8] such as the 2x2 recombiner shown in the upper inset of Fig. 5.

The *Single-ended* configuration also makes extensive use of optical 'hairpin' bends. Most of these are pairs of 90° corner bends (Fig. 5 lower inset), which if optimized correctly do not interact or require separate optimization as 'U' or 'S' composites. The waveguides are of the deep-ridge type (Fig. 1(b)) and are wide enough to support several guided modes; it is interference of these modes over the path of the bend that leads to low loss on the same principle as MMI couplers. A typical radius of curvature for these bends is 125µm. A semi-automated optimization routine is able to design for first-order mode residues below -30dB and loss below 0.1dB over the likely width uncertainty within the process.

The technique is also used for single-sweep 180° U- bends and 45° bends. Low loss (<0.05dB) has been experimentally verified in both 90° corner and 180° 'U' bends.

B. DP-QPSK and Four-Channel Arrays

The *Single-ended* principles have been extended to create compact arrays of four MZMs. Within the same RF footprint, the optical waveguides can be configured to provide either a simple array, with a single optical input divided between four independent modulator outputs, or a dual-polarization QPSK device, in which the MZMs are paired (I and Q) and their outputs combined to just two X and Y outputs.

The compact *Single-ended* GaAs modulator array was designed to use a new high-efficiency epitaxial layer specification, which provides $V\pi$ of 3V with a significantly shorter active length. This is helpful in reducing the effects of RF attenuation and velocity mismatch, and also facilitates a reduction in package length. A significant part of the package length is required to accommodate fiber-coupling arrangements and stress-relief, so concentrating this at one end is leads to a substantial space-saving. Fig. 6 (below) illustrates the resulting single-ended package and compares it to its OIF *fiber-inline* equivalent. In both cases $V\pi$ is a little under 3V using the epitaxial specification for which the chip was designed and modulation bandwidths are also similar at around 30GHz.

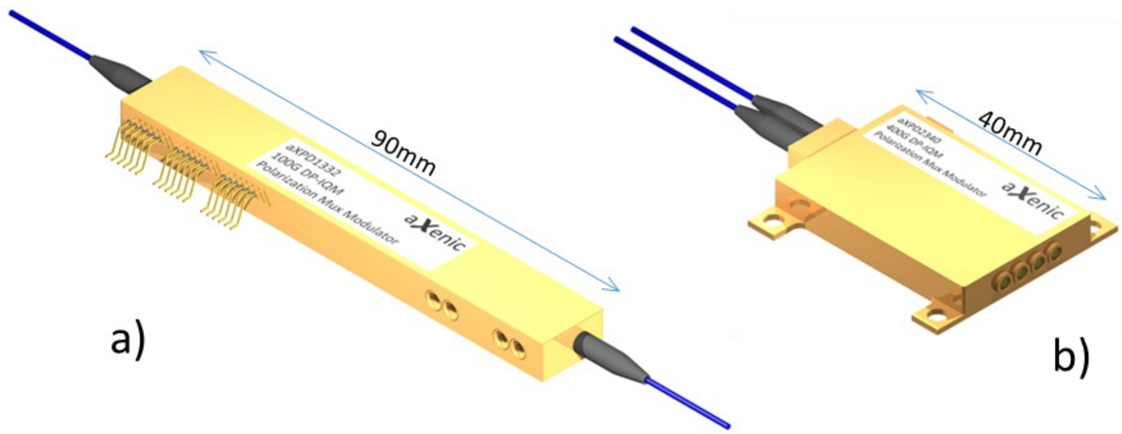

Fig. 6 a) OIF and b) single-ended MZx4 array packages to scale. Both have the same functionality and $V\pi$.

The main body of the single-ended package is 40mm long while the OIF standard package is 90mm long. This size and weight reduction is important for space applications

C. Electro-optic Frequency Response

The measured response for a module of this type is shown for all four channels in Fig. 7 (below). This device was designed for DP-QPSK digital coding, but could equally be an MZM array for part of a radar system in a space application. Comparing this with the single MZM response of Fig. 4 reveals the following features and differences:

1. Good average balance between channels. This is important in a multi-channel device and was the prime motivation behind the 'Straight RF' approach.
2. An extended response beyond 35GHz and continuing level to at least 40GHz.

The response droop beyond 35GHz, evident in Fig. 4, is not seen. This is mainly due to changes in RF-index intended to extend the bandwidth well beyond 40GHz. To achieve this in a dispersive structure, the RF Index is intentionally set low so that RF dispersion will establish velocity-match at higher frequency (above 45GHz). This generally results in the slightly depressed mid-range response seen here.

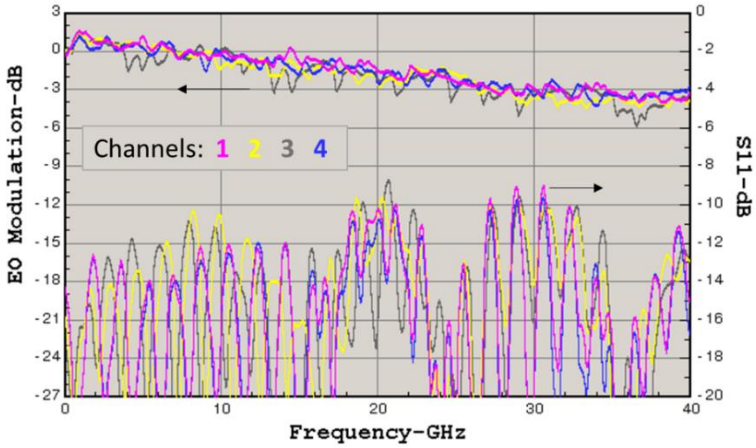

Fig. 7 Measured EO modulation properties of four-channel MZM array (Fig. 6)

V. CONCLUSIONS

We have introduced gallium arsenide (GaAs) and its related ternary compound AlGaAs as a coherent III-V semiconductor material system eminently suitable as a basis for electro-optic modulators for use in fiber systems for space. Already the material of choice for microwave electronics in aerospace and military systems (as well as cell-phone networks) GaAs is thoroughly qualified for harsh environments.

Broadband characteristics up to 40GHz, demonstrating a 35GHz bandwidth for $V\pi$ of 3V, have been presented for single GaAs Mach Zehnder modulators of conventional design, with a straight-through optical path and RF side-entry. Because these in-line designs are able to use a Y-branch MZ configuration they are relatively wavelength tolerant and are functional at both 1300nm and 1550nm. These modulators are highly applicable to current space applications which typically require frequencies up to 32GHz.

New designs for DP-QPSK and 1x4 MZ arrays have been introduced in which the RF path is straight but the optical path is single-ended, making extensive use of low-loss, compact 'U' bends in the GaAs optical waveguides. This allows multiple channels to have well-balanced RF inputs. These devices show extended modulation-responses which are flat from 30 to 40GHz and show excellent channel balance.

Acknowledgements

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