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50GHz gallium arsenide electro-optic modulators for spaceborne telecommunications

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ABSTRACT

Travelling-wave electro-optic modulators designed for V-band space applications using gallium arsenide guided-wave technology are presented. The designs feature a low-loss folded optical configuration giving straight-line RF access at one end of the chip, with all optical I/O via the opposite end. This configuration enables the close-packed monolithic modulator arrays needed for phased-array applications, contributes to high modulation bandwidths with low ripple by eliminating directional change in the RF feed arrangements and facilitates compact packaging. While only 1550nm designs are reported here, the AlGaAs material system is versatile, permitting modulators to be realized for a wide range of optical wavelengths, with particular advantage in drive-power at shorter wavelengths. Both single MZ and monolithic dual-parallel (IQ) modulators have been assessed up to 70GHz; bandwidths around 50GHz are achieved with low-frequency $V\pi$ of 4.6V. Typically, the folded devices are half the length of conventional format modulators and can accommodate 4 device arrays in the same width package.

Keywords: fiber optics, electro-optic modulators, V-band, 50GHz, GaAs, AlGaAs, III-V semiconductor.

1. INTRODUCTION

There is increasing interest in the advancement of optical methods for managing RF signals in space, with many applications for both ground-to-satellite and inter-satellite communications envisaged. There are obvious advantages to be gained from the enormous data capacity of multiplexed optical links, and with RF frequencies progressing towards Q/V bands, there arises a need for electro-optic modulators to operate at 50^+ GHz. The environmental credentials of gallium arsenide in the GaAs/AlGaAs III-V semiconductor material system are well known; the large semiconductor bandgap yields environmental stability and a useful degree of radiation hardness[1] and it is a natural choice for space-borne systems, with many desirable properties for RF devices which must survive and operate in harsh environments.

Travelling-wave electro-optic modulators in GaAs have similar properties of linearity to the better-known lithium niobate devices but can access higher bandwidths and lower drive-voltages within a significantly more compact footprint as well as offering enhanced stability. There is interest not only in discrete modulators, but also in arrays (monolithic or co-packaged) and higher functionality for modulation formats such as single-sideband (SSB), quadrature phase-shift key (QPSK), both of which conventionally use a dual parallel 'IQ' modulator configuration.

2. DESIGN ASPECTS

2.1 Loaded-Line MZ Modulator

The Mach-Zehnder modulator (MZM) consists of an optical splitter feeding into a pair of electro-optic waveguide phase modulators. The capacitive electrodes are set-up to operate in series push-pull[2], whereby a built-in back-to-back connection, via an in-grown n-doped backplane, creates a series-chain, halving the effective capacitance and splitting the RF potential, producing balanced, anti-phase phase-modulation contributions. Optical recombination produces a raised-cosine output-intensity function with no net phase modulation (i.e. zero chirp) and characterized by the half-wave (ON-OFF) voltage $V\pi$.

In travelling-wave versions of such a modulator, the aim is to match the velocity of a forward-propagating RF wave to the velocity of the optical modulation group which it is creating. Velocity-matching permits the modulation to accumulate monotonically along the entire length of the electrode, which needs to be long because electro-optic effects of most materials are very weak.

Our devices achieve velocity-match by means of a *capacitively loaded line* configuration. This slow-wave structure is required in semiconductor materials because, while the microwave and optical velocities generally have similar values, the ~50% free-space loading from the superstrate makes a pure coplanar RF wave run faster than the fully buried optical wave. The modulation electrodes are divided into a linear array of short segments isolated by passive spaces (see Figure 1 below). These sample the line-voltage via air-bridge connections to accumulate the modulation effect while adding shunt capacitance to slow the RF wave. For preference we use CPW (coplanar waveguide), which has double surface ground-planes. These are strapped together periodically by bond-wires to prevent the asymmetric loading generating higher-order RF modes. The loaded characteristic impedance and RF velocity are both subject to the same *slow-wave factor* (see section 5). In GaAs a good velocity-match can be designed to coincide with impedance a little under 50Ω.

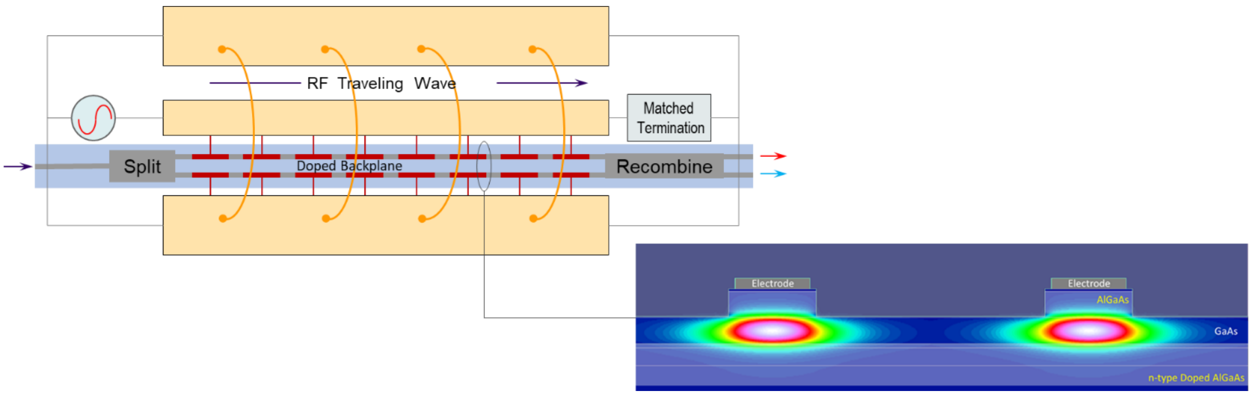

Figure 1 Schematic of loaded line travelling wave modulator based on strapped CPW transmission-line, with waveguide cross-section showing typical optical mode-profiles

It will be apparent from the schematic of Figure 1, that the essential co-linearity of RF and optical paths results in a topological conflict between the RF and optical inputs. In practice, the RF is usually input from the side of the device and bent through 90° while the optical line is kept perfectly straight. For frequencies above 30GHz, this is not good enough, hence our recent emphasis on optical path-folding so that the RF input run can be kept as short and straight as possible and is in-line with the optical travelling-wave section from the outset. This requires the extensive use of optical 90° and/or 180° bends. The availability of such bends enables extension of the GaAs modulator technology to more advanced configurations, such as IQ modulators (used for QPSK and single sideband formats) as well as monolithic arrays with all RF inputs at one end of the module and optical access entirely at the other (Figure 2).

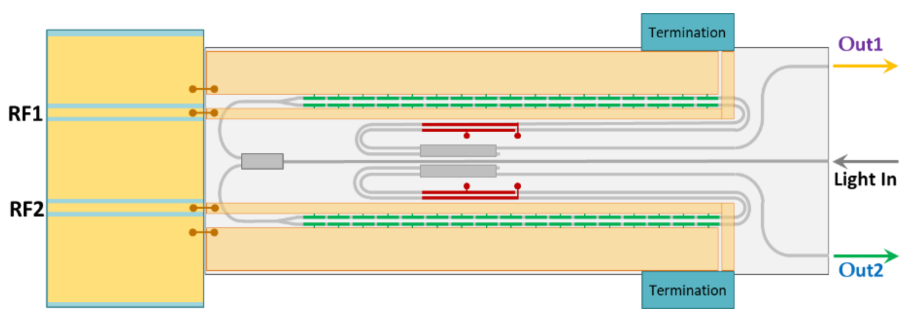

Figure 2 Folded-path dual-parallel modulator (1x2 array, SSB or IQ modulator) using 90° and 180° waveguide bends.

Arguably, monolithic arrays of more than two modulators would hardly be possible without such provision. It allows four or more channels per chip with only minimal additional complication, and in a package of similar size.

This topology is particularly suitable for phased-array applications with fiber-optic antenna-head remoting. Within the modulator package itself there are further gains in compactness due to the concentration of space-hungry fiber interfaces at one end.

Clearly such a concept is not viable if the 90°corner and 180° 'U' bends contribute more than a negligible loss, or cause mode-coupling. These need to be low-loss and designed carefully to maintain good optical characteristics. There is also a potential additional overhead of straight waveguide loss from the input-run which, as illustrated in Figure 2 is largely parasitic. In practice, this length of waveguide can be used to accommodate DC phase control electrodes, reducing the lengths needed in the output foldback sections.

3. FOLDED-PATH OPTICAL MODULATOR DESIGN

3.1 'Matched' Corner Bends

The waveguides used for the bend-sections are of the deep-etched ridge type. Unlike the rib waveguides illustrated in Figure 1, these are etched fully through the GaAs core-layer and have a very high lateral index-contrast (both types of waveguide are used within the device for different purposes, with low-loss taper transitions between). Thus, bend behavior is determined by mode-coupling and mode-interference mechanisms rather than by radiative loss.

Bend-design emphases found in literature include the matched bend[3] (in which the total path-length is matched to a dominant intermodal beat-length), and gradation of curvature, for example using multi-parameter geometric functions with computer-optimization routines; e.g. cubic-splines[4], euler-spiral[5] or other non-explicit function. Our bends use both principles, but with our own proprietary functions and methods to identify the lowest-loss and most process-tolerant designs.

Our design simulation method closely replicates the way the bends are constructed in the CAD layout, as a succession of angled straight segments. Successive pivoting of the graphics coordinate system allows the bend to be displayed semi-realistically as in Figure 3, showing up a 'whispering gallery' type of behavior.

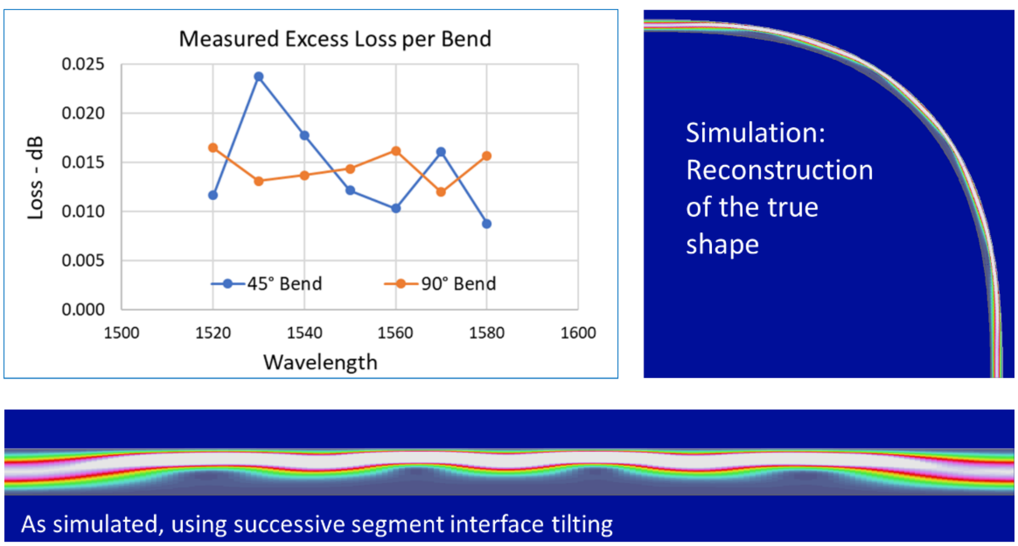

Figure 3 Simulation detail and measured losses of optimized bends.

While it is possible to devise one-piece U or S bends it is more usual to base the waveguide configuration on a concatenation of identical standard optimized bends. These are mainly 90° corner bends, but other types, e.g. 45° (allowing an orthogonal mutual crosspoint) also have their uses. Our optimization of a bend-profile is not based on simple best performance (e.g. lowest loss, least higher-mode residue) but on worst-case performance over a range of likely process and wavelength variation.

Different bend optimizations have been validated for several recent device designs using dedicated test waveguide structures. Each new device design carries such ancillary test-sets for the exact bend used within the design, and test bends typically comprise concatenations of many corner-bends. Losses are measured by a fabry-perot resonance technique[6] using test-pieces without antireflection coatings. Without exception, the excess loss per bend has been measured at between

0.012dB and 0.02dB, averaging about 0.015dB (Figure 3), consistent with models, and with low sensitivity to wavelength as seen in Figure 3.

3.2 Couplers, Splitters and Recombiners

Most guided-wave optical circuits will require splitters and recombiners to perform basic interferometry. Historically, Y-branches and waveguide directional-couplers were the first port-of-call for these functions – and this is still the case for lithium niobate modulators based on diffused channel waveguides. In semiconductors, directional couplers are problematic because the weak lateral confinement required demands shallow etches with consequent high sensitivity to etch depth.

The preferred multimode interference (MMI) couplers[7] are lengths of wide, deep-ridge waveguide with suitably placed waveguide ports. When etched fully through the GaAs core-layer the properties are stable against any variability in the etch-depth, though a tight tolerance on the width is mandatory. The MMI concept makes use of the tidy geometrical relationship between the propagation velocities of waveguide modes when the walls are of high reflectivity (so that all modes are subject to the same effective width) – a condition well satisfied by the deep-ridge GaAs waveguides used.

Any launch condition can be decomposed as a superposition of the MMI modes and radiation. With the launch phase-relationship restored cyclically at multiples of a fundamental beat-length along the MMI waveguide, lens-like re-imaging of the launch profile results. Most useful is the fact that a double image appears at half this re-imaging length. This provides 2x2 split and recombination functions in a process-tolerant structure.

Figure 4 shows propagation modelling on a 2x2 MMI recombiner which has been used in our GaAs modulator designs; these can also be used for the optical split function. 2x2 MMIs of this type provide a 1:1 split/recombination ratio which is closely maintained even when the geometry (or wavelength) is far from the design-center; the excess loss can be significant before the split-ratio is degraded. This means that (unlike the directional-coupler) the modulator extinction-ratio is maintained out of band, even if loss increases.

Much of the subtlety in guided wave design using components such as these lies in choice of geometry to maximize tolerance to process and wavelength variation. As with bend designs, MMIs are dimensioned to this end.

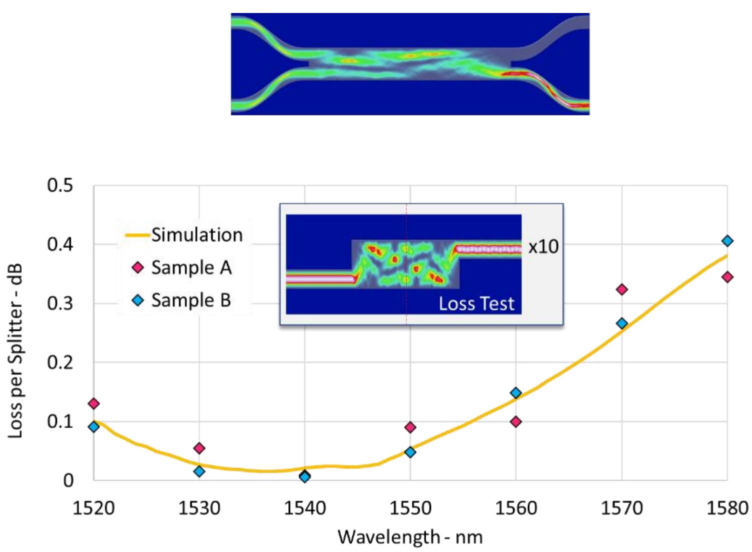

Figure 4 Simulation and loss measurements on MMI optical recombiners

The chart in Figure 4 compares the measured excess loss with simulation for one split or recombine unit (without I/O bends). The test-set for this used a concatenation of 10 full-cross MMI units (the simulation also calculates the full concatenation). Excellent agreement with measurement is obtained; moreover, the excess loss of an optimized MMI is clearly very low.

Despite the virtues of MMI couplers, there remains a sensitivity to wavelength in terms of excess loss (though not split-ratio) which limits the modulator design to a specific wavelength band. Broader waveband operation, for example encompassing 1300nm and 1550nm bands, would require the exclusive use of a non-interferometric split/recombine structure such as the Y-branch. For this reason, we continue to improve our Y-branch designs (Figure 5). These are of low loss but do not offer the excellent process tolerance and reliably high modulator extinction-ratio of MMIs.

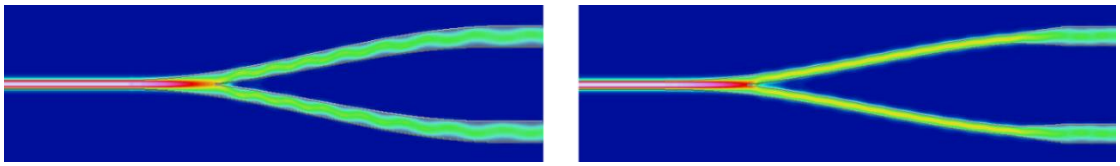

Figure 5 Y-branch simulations contrasting sub-optimal and optimized tapering of the divergent waveguides.

4. MODULATORS FOR SHORT WAVELENGTHS

There are several reasons to consider wavelengths other than the telecoms band around 1550nm for space applications (e.g. the availability of high-power solid-state lasers at 1064nm). Generally, without long-haul fiber links there is no special reason to prefer 1550nm other than to utilize off-the-shelf components developed for terrestrial systems. One further powerful reason to move to shorter wavelength is the much-reduced drive-voltage which can be obtained from a GaAs/AlGaAs modulator.

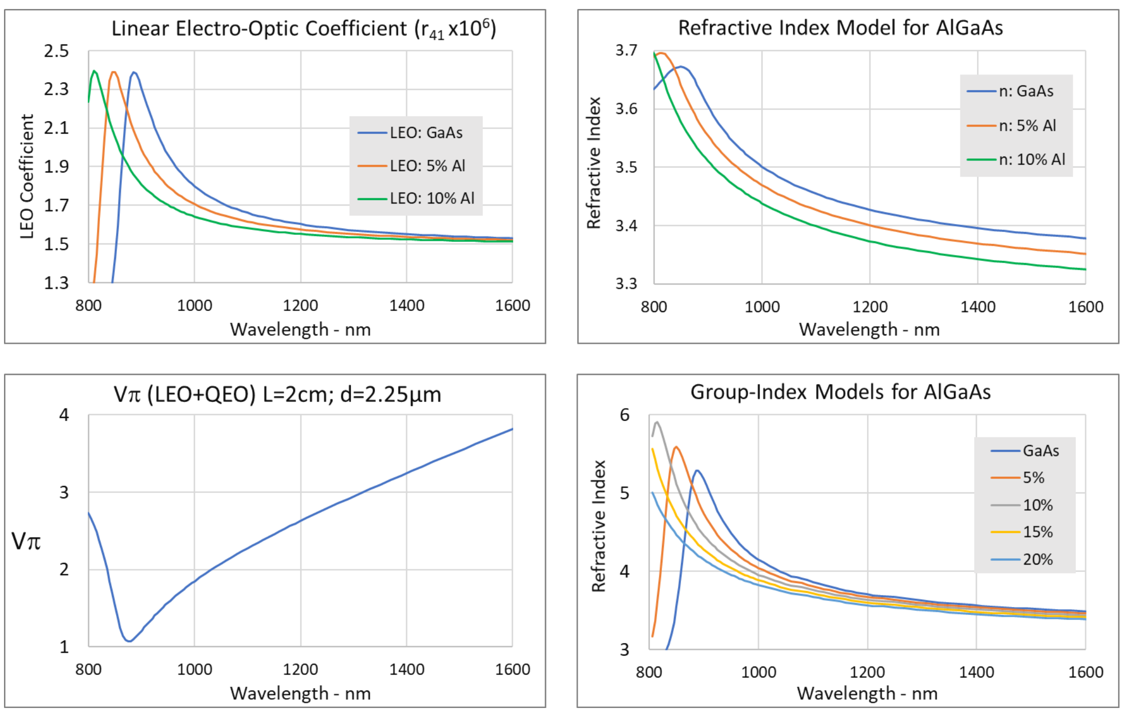

Figure 6 Electro-optic data relevant to short-wavelength AlGaAs modulator design [8, 9, 10] with derived example Vπ

Two reasons for this can be seen from Figure 6 (above). Both the linear and quadratic electro-optic coefficients rise sharply towards the semiconductor band-edge (874nm in GaAs). This advantage is valuable well before electro-absorption becomes significant approaching the band-edge. A related benefit accrues from the dispersion of the refractive-index (n), which also rises at shorter wavelengths: the electro-optic effect is proportional to n^3. Finally, there is a direct scaling with wavelength itself when the electrode length is fixed.

The versatility of the AlGaAs material system arises from the fact that GaAs and AlGaAs are nearly lattice-matched for all AlGaAs compositions. Thus, to design for even shorter wavelengths (e.g. below 1000nm) the aluminium level (x in $Al_x Ga_{1-x} As$) can be increased without serious design or process modifications.

The example calculation for Vπ in Figure 6 may be regarded as an upper limit to the Vπ as additional effects from free-carrier sweep-out (not included here) provide an important further enhancement. Unlike carrier-injection, sweep-out is a fast majority-carrier process arising from the definition of capacitance, so remains relevant to the highest frequencies.

The calculation for Vπ in Figure 6 shows a factor of two reduction from ~1600nm to ~1000nm, representing a four-fold reduction in RF power. Other modelling confirms that designs down to 1000nm are achievable and can yield benefits over longer wavelengths in overall performance.

5. VELOCITY MATCHING AND RF DESIGN

A major motivation for optical path-folding is to preserve the integrity of the RF feed to the active modulation zone. The path folding allows the simplest, highest frequency, interface from the RF package and connectors and allows the RF interconnection as arrays to be managed in a parallel arrangement.

Even the best RF feed is of little use if the chip design makes poor use of it. A fundamental limitation to the chip bandwidth comes from the inherent RF loss, due primarily to the coplanar metal resistance and the backplane shunt conductance. This is unavoidable and will tend to bias a design for 50^+ GHz towards shorter solutions with tighter field confinements and higher electro-optic slope.

Additionally, good velocity-matching (optical group-velocity to RF phase-velocity) must be achieved. If the design is set-up for 'RF-fast' at low frequency, RF dispersion will ensure that velocity-match occurs at some higher frequency, where the rising RF-index intersects the fixed optical group-index. Good computational models for these parameters are required to ensure that this intersection occurs near the highest frequency of interest. As with RF loss, velocity-match is less critical on a shorter length.

The base, low-frequency velocity-match is determined by the slow-wave factor $\sqrt{1 + {C_L}/{C_c}}$, where $C_L$is the loading capacitance from the electrodes and $C_c$is the unloaded coplanar capacitance – both per unit length. Thus, the velocity-match is set by both the coplanar geometry and the electrode properties, either built into the epitaxial layer-structure (mainly the depletion thickness 'd') and others in the layout. – e.g. width and segmentation filling-factor[11]. For high-frequency operation the RF dispersion is equally important. Dispersion is influenced by many factors, including the coplanar line geometry, segmented electrode properties and CPW ground-strap bonding (Figure 1). The RF dispersion cannot be reliably calculated without reference to at-least 2.5D and preferably full 3D RF computer models.

5.1 Velocity-match at short wavelength

Optical dispersion must also be considered when re-designing for a new wavelength or for a broad wavelength band, as this determines the waveguide group-velocity. The RF power advantage of short wavelength operation is very significant, as has been shown. Near the semiconductor band-edge, dispersion is high, resulting in significantly enhanced group-index values (see Figure 6); this strongly influences the design approach for a short-wavelength V-band modulator and requires a different velocity-matching strategy compared to 1550nm. A higher slow-wave factor is required, and this can be readily achieved with the flexibility of the GaAs/AlGaAs semiconductor system by using a coplanar base-structure of increased impedance, by adjusting the waveguide geometry and by specifying epitaxial layers with thinner depletion and increased aluminium.

6. 50 GHZ MZ AND IQ MODULATORS

Both single MZ and dual-parallel (IQ) modulators have been assessed, to a common 1550nm design. The single MZ is essentially one half of the dual IQ device, only benefiting from slightly lower loss due to the lack of outer (parent) split and recombine elements. In terms of RF design, they are identical. The objective in this design was for 50^+GHz bandwidth with Vπ below 5V. This has been achieved. Compared with our standard 35GHz 'straight-through' design with its Vπ of 3V, this more relaxed drive-voltage target allowed a substantial shortening of the active travelling-wave section to facilitate achieving the bandwidth. This, and the path-folding enabled a halving of the package length, down to 45mm from 78mm.

Figure 7 below compares the frequency responses of the two single MZ devices. The folded-path modulator shows a greatly extended response to 70GHz with 3dB bandwidth near 50GHz and has a notably smoother response due to the RF feed improvements. The measured DC Vπ is typically 4.6 ±0.1 volts.

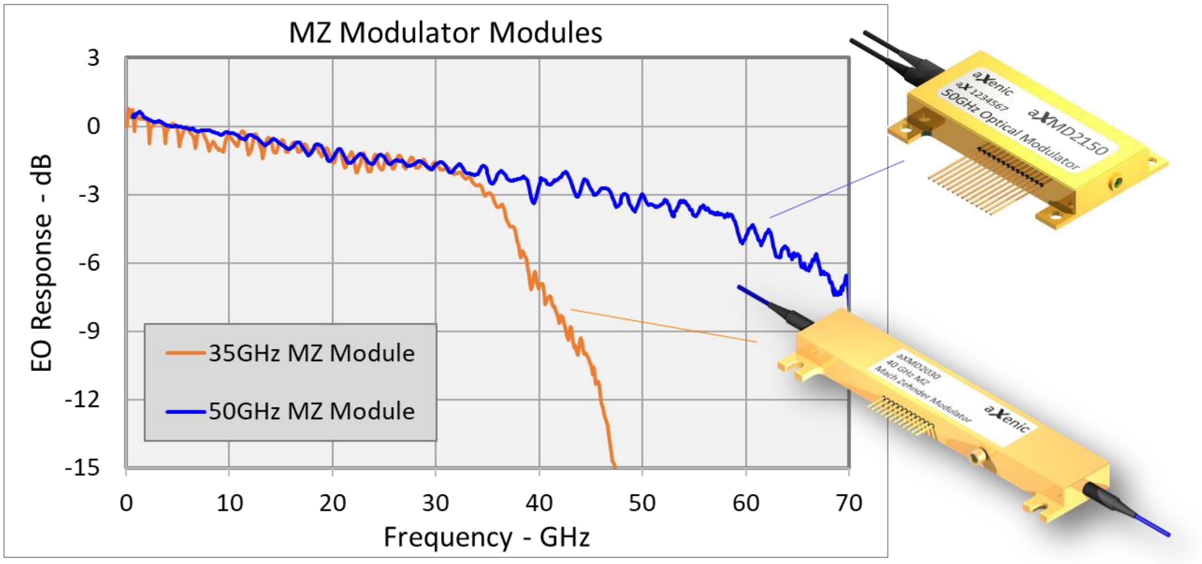

Figure 7 Measured frequency-response of 35GHz conventional and 50GHz folded-path GaAs MZ modulators at 1550nm

The dual-parallel (IQ) version of the design has very similar characteristics, as illustrated in Figure 8 below.

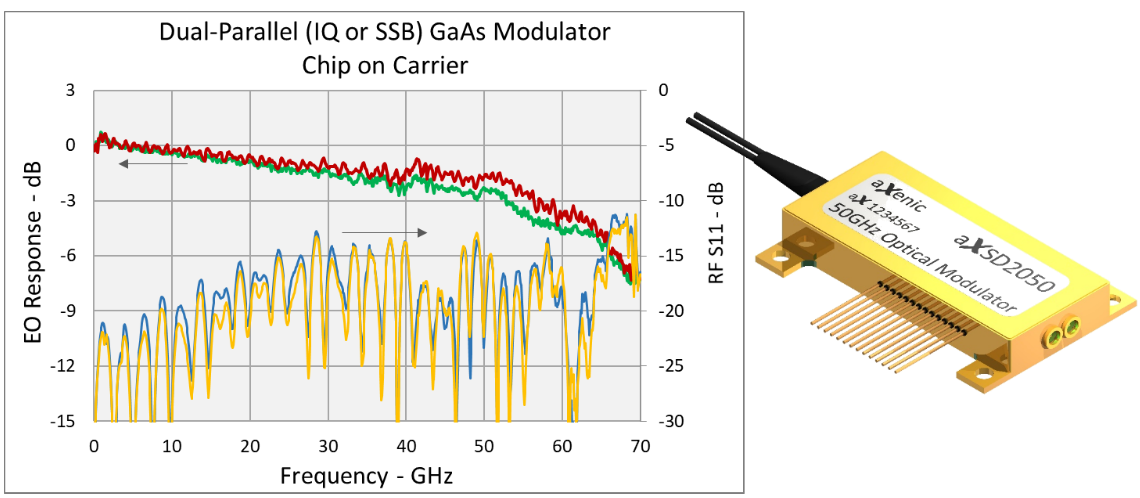

Figure 8 Measured electro-optic RF characteristics for both I and Q channels of a 50GHz folded-path GaAs IQ modulator. These are chip-on-carrier measurements.

7. CONCLUDING SUMMARY

Folded-optics, travelling-wave, GaAs electro-optic modulators have achieved 50GHz bandwidths with Vπ of 4.6V in both single and dual-parallel (IQ) configurations designed for 1550nm. The folded optical configuration allows straight in-line RF access to the active section, contributing to high modulation bandwidths with low ripple by eliminating directional change in the RF feed arrangements. This also facilitates compact packaging and improves overall access by segregating the optical interfaces to one end of the module with the RF interfaces at the other end. The folded arrangement also leads to much more compact packages since the modulator chip is typically much shorter; moreover, the space-hungry fiber-interfacing arrangements are concentrated at one end, while considerations of RF loss encourage minimalist RF interfacing at the other.

The AlGaAs material system is versatile, permitting designs to be realized for a wide range of optical wavelengths. We have presented basic design data to demonstrate the potential for significant advantage in terms of drive-power at shorter wavelengths, particularly at 1064nm or shorter. We estimate a four-fold reduction in RF drive power in a modulator designed for 1064nm comparted with a similar active length at 1550nm.

The IQ modulator reported here is a specialized example of a generic 1x2 modulator array. This is readily extended to 1x4 or larger arrays using the folded-optical method. Current packages have sufficient space for these larger arrays without needing to add to the width of the package. Ultimately, with larger arrays, the number and spacing of the RF connectors, rather than the optical chip size would be the main driver towards wider packages.

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