

# Manufacturable GaAs Electro-Optic Modulators with Improved Dynamic Range

J. M. Heaton, A. Miller, G. Murdoch, Y. Zhou, P. Jiang<sup>†</sup> and D. R. Wight.  
Filtronic Compound Semiconductors Ltd (FCSL), Newton Aycliffe, DL5 6JW.

<sup>†</sup> Now at the University of Bristol.

## Abstract

*The aim of this programme is to develop optimized optical modulators that can be manufactured and used as the critical component in generic high spurious free dynamic range (SFDR) RF-photonics transducers. We describe two types of linearised electro-optic waveguide modulator optimized for the transmission of RF signals with a high SFDR on optical fibres and present measured results to demonstrate their performance.*

Keywords: linearised modulator, electro-optic, GaAs, optical waveguide, RF optical link.

## Introduction

By making use of the very high frequency of light as a carrier wave, the transmission of RF on optical fibre allows broadband microwave signals to be routed around or between military platforms with very high fidelity [1-7]. For certain applications, RF-over-fibre is the only method that can transmit such signals with the required negligible dispersion and frequency dependent loss that can be achieved by using a 200 THz carrier wave. These applications include: 1) transmission of RF to remote antennas; 2) distribution of the local oscillator in a phased array radar; 3) true time-delays for jamming, false target generation and squint-free phased array radar; 4) direct optical sampling and digitisation of microwave signals for frequency analysis.

The main reason why RF-on-fibre is not used more widely in military systems is that the spurious free dynamic range (SFDR) is not high enough for many of these applications [1-7]. The aim of this programme is to overcome this limit and to develop a generic broadband high SFDR transceiver that can be used for a wide range of RF-photonics applications both in

military and commercial equipment.

The component which limits the SFDR is the optical modulator that superimposes the RF signal on to the light wave carrier. The most accurate type of RF optical intensity modulator is based on an electro-optic waveguide Mach Zehnder interferometer which gives a very precise sinusoidal light-intensity-against-voltage (L-V) response rather than an ideal linear one.

In this paper we describe our approach to make a more linear electro-optic modulator to give a higher SFDR. Our target is to make a broadband modulator with an SFDR that is 20 dB higher than a Mach Zehnder modulator can achieve [1]. The device must also be manufacturable. Which means in practice that the linearity must be controllable using one or more electro-optic tuning electrodes. We describe the design, fabrication, packaging and testing of two types of gallium arsenide electro-optic waveguide tuneable linearised modulators: one based on a symmetrically fed (Y-fed) directional coupler [1,4] and the other based on a four-guide version of the standard Mach Zehnder modulator [1,2,6]. The tuning method in both devices is novel and original, and currently allows a >5 dB

improvement in the SFDR to be achieved reliably, with signs that more significant improvements can be achieved with more precise control of the tuning voltages.

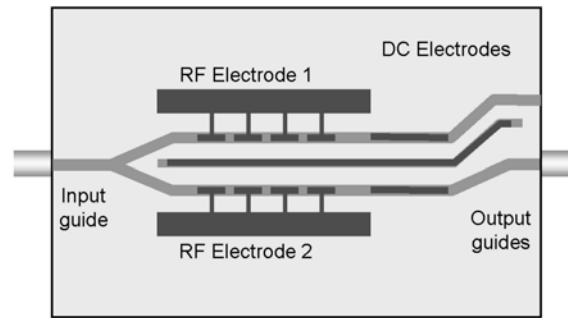
### Tuneable Y-fed Directional Coupler

To make a linear electro-optic modulator, the light-intensity-against-voltage (L-V) response must be modified from the very precise sinusoidal response given by a conventional two-guide Mach Zehnder interferometer. This is achieved by effectively adding another very precise sinusoidal L-V responses with a different “frequency” (i.e. a different on-to-off drive voltage  $V_\pi$  [1]) in the correct amplitude and phase to make the overall L-V response closer to a straight line.

One promising approach is to use a symmetrically fed (Y-junction or Y-fed) optical waveguide directional coupler [1,4]. The two main waveguides are close enough together that the light couples backwards and forwards between them. This generates a low- $V_\pi$  route through the device (followed by a small fraction of the input light which remains in the same waveguide all along the coupler) and a high- $V_\pi$  route (followed by most of the input light which couples from one guide to the other and consequently experiences a reduced RF-induced electro-optic phase shift). The coupler naturally adds these contributions in the correct phases but the amplitude of the different contributions has to be controlled very accurately. This involves controlling the rate of coupling of light between the guides to a very high precision. In our previous paper [1] we achieved this by using an array of different devices (not tuneable) with different coupled guide pitches. This was not practical because it involved making many different devices, selecting the most linear ones and discarding the rest.

A novel approach to tuning this type of

directional coupler device was analysed theoretically, using optical waveguide design software, and appeared to give a very simple control of the coupling rate between the guides without compromising the linearisation process. This involved using a third electro-optic waveguide between the original two RF addressed electro-optic guides (as shown in Figure 1).



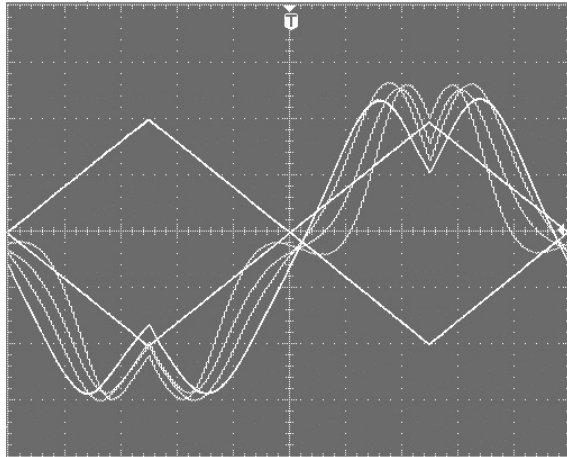
**Figure 1.** Schematic diagram of an electro-optically tuneable Y-fed directional coupler linearised modulator [1,4]. The narrow electro-optic waveguide in the centre of the device is used to control very precisely the rate at which light couples between the two wider waveguide.

The extra waveguide can be used to change the refractive index between the two outer guides, which changes the coupling rate with very high precision.

Devices of this type were designed and fabricated using Filtronic’s gallium arsenide electro-optic modulator process [1,2], which is based on a slightly-modified high volume p-HEMT process. For making linearised modulators, it is particularly important to use a very reliable and repeatable fabrication process because the waveguide parameters have to be very accurately controlled. The wafers were scribed and broken into 20 mm x 20 mm tiles, the waveguide facets were anti-reflection coated, and the tiles were diced into individual modulator die.

A set of five travelling-wave [1,2] electro-optic tuneable Y-fed directional coupler

modulators were made on each tile. Each device had a different coupler pitch to allow for variations of the waveguide etch depth. The modulator die were tested individually and then packaged with RF K-connectors and standard optical fibres on the input and output guides.



**Figure 2.** Four measured light-intensity-against-voltage (L-V) responses for a tuneable Y-fed directional coupler modulator. The triangle-wave lines are the voltages applied to the two signal electrodes of the Y-fed directional coupler. The four L-V responses are for the tuning voltages 1) -10.5V, 2) 0V, 3) 20 V and 4) 30V.

Figure 2 shows the result of measuring the L-V response with different tuning voltages applied to the central waveguide. The figure shows the screen of an oscilloscope that was recording the time dependence of the voltages applied to the RF electrodes of the device and the light intensity emerging from the output fibre.

It is clear from these results that the tuning voltage can be used to change the L-V response from non-linear to linear through a well-defined sequence of L-V response shapes. These results show clearly the effect of adding different amounts of light that passed through the high- $V_{\pi}$  route with the light that passed through the low- $V_{\pi}$  route. The ratio of the optical powers passing through the different routes is

controlled by the tuning electrode. The L-V response shapes are very similar to those obtained by changing the directional coupler guide pitch as described in Reference 1.

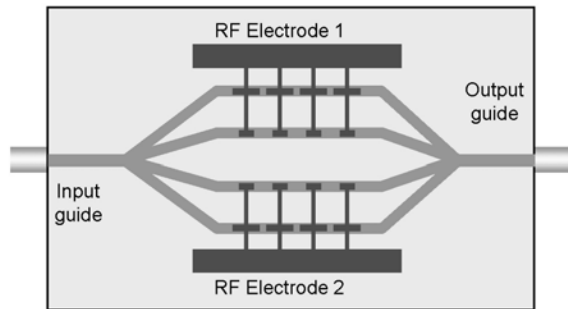
There are two advantages of using this tuning method. The first is that it relaxes the sensitivity of the devices to etch depth variations, which inevitably occur in practice. The second is that it allows the device to be tuned continuously (rather than in the discrete steps achieved by using different fixed guide pitches [1]) to optimise the SFDR precisely. Also the tuning method is relatively straight-forward to use in practice because the tuning electrode should only affect the third harmonic.

The main disadvantage of this device design is that, because the linearisation occurs along the length of the travelling-wave electrode, it will depend on the RF loss along the electrode and so will depend on the microwave frequency. The SFDR can be optimised around any single frequency by setting the tuning electrode voltage to the required value. However, the SFDR will not necessarily be optimised at other frequencies.

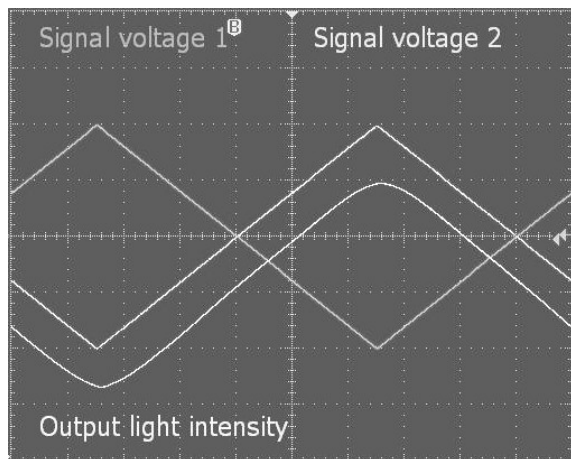
#### Four-Guide Mach Zehnder Modulator

A device that should avoid this dependence of linearisation on frequency is shown schematically in Figure 3. This is a variation of a Mach Zehnder modulator in which two extra interferometer guides are added to supply the linearisation correction term. The key difference between this device and the Y-fed directional coupler is that the RF signal modulates the optical phases in all four guides and then combines the four light beams with the correct amplitudes and phases to give a linearised response [1,7]. The modulation and the linearisation processes are kept separate, in different parts of the device, so that the

linearity (and SFDR) does not depend on the travelling-wave line loss.



**Figure 3.** Schematic diagram of a four-guide Mach Zehnder linearised modulator [1,7] – for broadband high SFDR operation.



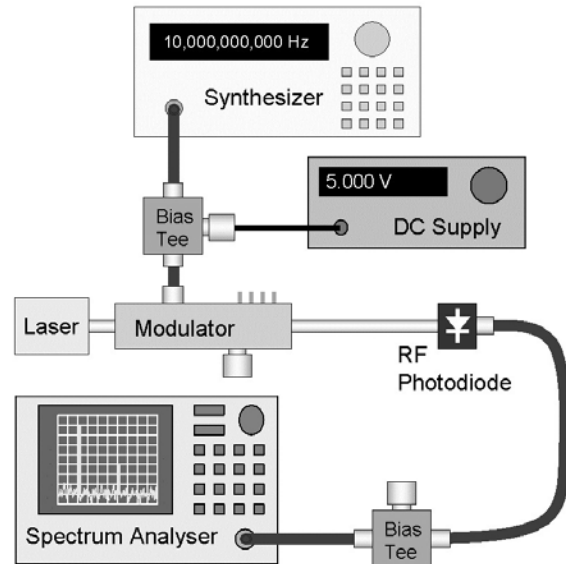
**Figure 4.** Measured light-intensity-against-voltage (L-V) response of a Four-guide Mach Zehnder linearised modulator.

Figure 4 shows the measured L-V response for a four-guide Mach Zehnder linearised modulator. It shows the screen of an oscilloscope recording: 1) the triangle wave voltages applied to the RF electrodes, and 2) the optical intensity from the output fibre. It is clear that the L-V response is more linear in the central region than the sinusoidal response of a conventional two-guide Mach Zehnder would be.

### RF Measurements of Dynamic Range

Fully packaged modulators of the three

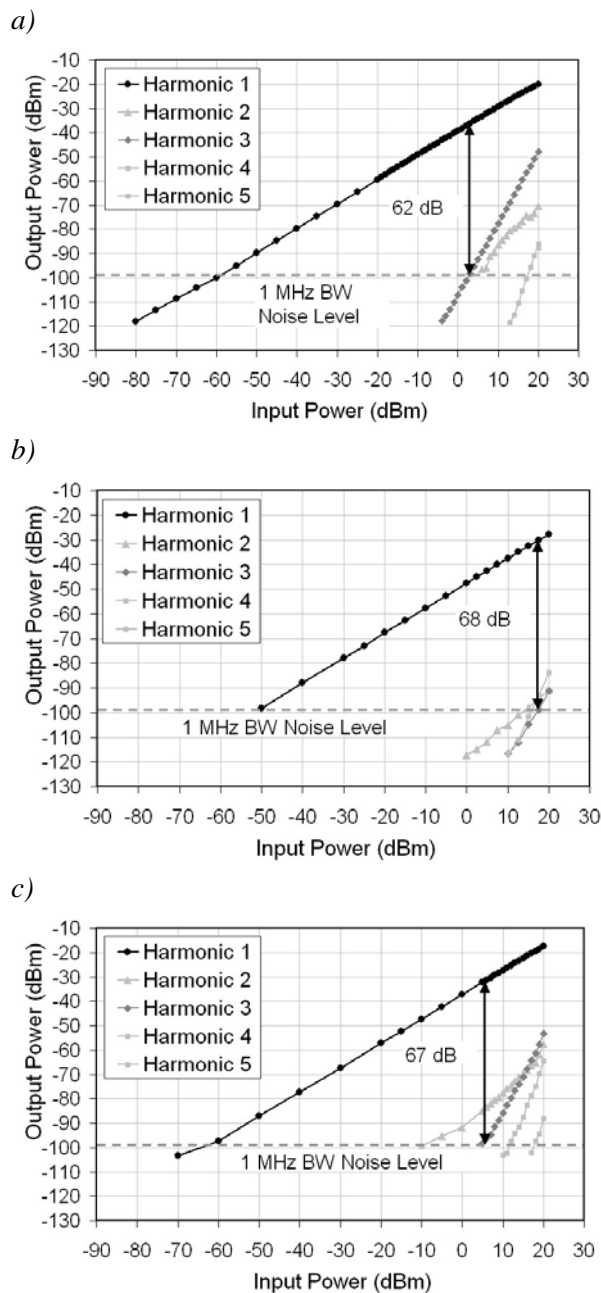
different types (two-guide Mach Zehnders, Y-fed directional couplers and four-guide Mach Zehnders) were tested to determine their spurious free dynamic range (SFDR).



**Figure 5.** Schematic diagram of the test equipment used to measure the spurious free dynamic range (SFDR) at different frequencies.

A diagram of the test equipment used to measure the SFDR is shown in Figure 5. Light from a continuous wave laser was passed through the modulator and into an RF photodiode. For some measurements an erbium doped fibre amplifier (EDFA) was placed just before the photodiode to amplify the signal so that the total optical power incident on the detector was constant. The RF signal was generated by a synthesizer and was passed through a bias-tee before entering the device via the K-connector. The bias-tee was used to add a DC voltage to the RF signal to set the modulator at quadrature. The linearised modulators also required extra tuning voltages from DC power supplies. The signal from the RF photodiode passed through a bias-tee before entering a spectrum analyser. The devices were driven at fixed frequencies (typically between 1 and 2 GHz) and the power of the RF fundamental frequency and the higher

harmonics were measured on the spectrum analyser for different input RF power from the synthesizer. The results are shown in Figure 6 for the three types of modulator.



**Figure 6.** Graph of the measured output power in different harmonics from RF-photonic links with different types of modulator: a) Mach Zehnder; b) Tuneable Y-fed directional coupler; c) Four-guide Mach Zehnder

Figure 6a) shows the measured output

power from the photodetector in the different harmonics from a conventional Filtronic gallium arsenide two-guide Mach Zehnder modulator, plotted against input power into the modulator. The fundamental frequency was 2.0 GHz so the higher harmonics (second to fifth) were measured at 4.0, 6.0, 8.0 and 10.0 GHz. The first, third and fifth harmonics behaved exactly as predicted theoretically indicating that the Filtronic GaAs Mach Zehnder modulator has an L-V response that is very accurately sinusoidal. The spurious free dynamic range (SFDR) is defined as the input power (in dBm) at which the highest power spurious signal appears above the noise and the input power (in dBm) at which the fundamental harmonic appears above the noise. In this example the third harmonic is the highest power spurious signal.

This definition implies that the SFDR depends on the noise floor, which in turn depends on the resolution bandwidth of the spectrum analyser. We have chosen a noise level of  $-98$  dBm, which corresponds to the background noise level in a 1 MHz bandwidth. Using this figure the SFDR of a conventional Filtronic gallium arsenide Mach Zehnder modulator is 62 dB in a 1 MHz bandwidth (or more precisely  $62$  dB/MHz<sup>2/3</sup> which is equivalent to  $102$  dB/Hz<sup>2/3</sup>).

Radar typically needs SFDR values of 90 dB or higher, but this is into narrower bandwidths. We have demonstrated that, if the bandwidth is reduced to 1Hz, the third harmonic can be 92 dB below the fundamental frequency when it appears above the noise floor.

Figures 6b) and 6c) show the corresponding results for the Y-fed directional coupler and the four-guide Mach Zehnder linearised modulators. The measured SFDR values for these devices are  $68$  dB/MHz<sup>2/3</sup> and  $67$  dB/MHz<sup>2/3</sup> respectively, where the SFDR is based on the third harmonic being the most

significant spurious signal. In both of these figures, the second harmonic is actually higher than the third harmonic, but the second harmonic is caused by a completely different mechanism (the quadrature point bias voltage) and can be minimised further than shown in these results using a feedback circuit.

### Conclusions and Future Work

Note that although the third harmonic SFDR improvements of 6 dB and 5 dB are not high (compared to the  $62 \text{ dB/MHz}^{2/3}$  Mach Zehnder result), there is evidence from these results that more significant improvements can be made. The Mach Zehnder results are in excellent agreement with theory and so are very close to the fundamental limit that can be achieved with this type of device. The minimum possible third harmonic power for a conventional Mach Zehnder modulator is very well defined and cannot be reduced further. The advantage of both types of linearised modulator is that the third harmonic can be changed and can be minimised beyond the fundamental Mach Zehnder limit as shown in Figures 6a) and 6b). Suppressing the third harmonic below the Mach Zehnder fundamental limit by even a few dB is significant and there are signs that further improvements can be made.

We have demonstrated fully packaged gallium arsenide electro-optic waveguide linearised RF modulators using two novel designs. We have demonstrated that both designs have the critical third harmonic suppressed below the fundamental limit that can be achieved with a conventional Mach Zehnder modulator. Future work includes: 1) making a more thorough analysis of the RF bandwidth of the SFDR of the different types of linearised devices; 2) optimising the tuning mechanism and reducing stray light in the waveguide path to achieve higher dynamic range improvements; 3) developing a multi-voltage stabilisation

method with feedback for maximising the SFDR of the linearised modulators; and 4) making devices with reduced  $V_\pi$  to minimise the RF loss through the optical link. Using the optimum linearised modulator design with a compact stabilisation feedback circuit, our aim is to develop generic (and custom) high SFDR RF-on-fibre transducers, initially for trials in military systems, ideally followed by design into in-service military equipment.

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