

Linearised Gallium Arsenide Electro-Optic Waveguide Modulators

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Abstract

For transmitting high dynamic range broadband microwave signals around or between military platforms it can be essential to use an RF-on-optical-fibre link because this is the only way to avoid distorting the original signal by dispersion or frequency dependent attenuation. Such links require very high performance electrical-to-optical transducers that can convert the RF voltage into an optical intensity with very high precision and linearity. In this presentation we summarise the results of our programme to develop broadband microwave electro-optical modulators with the unprecedented linearity that currently can only be achieved by using a state-of-the-art high-volume gallium arsenide fabrication plant.

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

Introduction

For certain applications that involve faithfully transmitting high dynamic range broadband microwave signals around or between military platforms it is essential to use an RF-on-optical-fibre (“RF-photonic”) link [1-8]. Currently, for example, to transmit a 20 GHz bandwidth signal from one end of a frigate (or aircraft carrier) to the other (e.g. for a cross-eye jammer), an RF-photonic link will give not only significantly lower signal distortion than a coaxial cable, but will also give less overall loss at the higher frequencies. Other applications of RF-photonic links 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 [1-3].

As laser, modulator (Figure 1) and photoreceiver technology progresses to allow higher optical power levels to be used, the performance of RF-photonic links will significantly out-perform coaxial

cables, waveguide, free-space RF transmission or any other purely electrical transmission method, even for much shorter propagation distances. This is because a modulator up-converts the broadband RF signal to the very high frequency (200 THz) of the optical carrier wave so that in optical terms it becomes a very narrow-band signal and does not suffer from dispersion.



Figure 1. A packaged 100 MHz to 20 GHz electro-optic waveguide modulator [RFMD (UK) Ltd.]

With the development of higher power, lower noise lasers, the applications of RF-photonic links will have advantages over other RF propagation methods purely because their loss is almost independent of propagation distance (0.2 dB / km). So even for narrow-band signals there will be

applications in which an optical link can outperform conventional RF transmission methods such as a coaxial cable (~1000 dB / km at 20 GHz). However, despite the clear benefits of RF-photonic links, they are not widely used at present in military hardware and this programme has concentrated on addressing the main issues that prevent the current technology from being used in more military systems.

The main reason why RF-photonic links are not more widely used in military systems is that with current component technology the spurious free dynamic range (SFDR) of the electrical-to-optical transducer (modulator) is not thought to be high enough for many military applications. This is partly because the critical components used in the link have to be operated close to their maximum optical power limits to achieve a potentially useable SFDR. However it is also because the SFDR of an RF-photonic link is a more difficult parameter to understand and specify compared to that of conventional microwave transmission methods. Also the procurement of critical components is difficult and will usually involve developing custom modulators optimised to the particular signal power levels required.

Because the SFDR (and link loss) depends on the optical power incident on the photodetector, as well as the system receiver bandwidth and the very well defined non-linearity of a conventional electro-optic waveguide Mach Zehnder (MZ) modulator, it is difficult to produce a generic RF-photonic link that can be used in any application in the same way as a coaxial cable can for example. The component design, including 1) the laser power and relative intensity noise (RIN), 2) the modulator drive voltage ($V\pi$), loss and maximum optical power limit, and 3) the photodetector size, responsivity and maximum optical power limit, all need to be optimised for each specific application. This is because to achieve the required RF-

photonic link performance, these components all have to be operating close to their current technological limits - especially their maximum optical power limit. For these reason there is a reluctance of conventional microwave systems designers to consider RF-photonic technology in practice. The main aim of this programme has been to increase the pull-through of RF-photonic technology by addressing the critical component issues and in particular by attempting to make and demonstrate high performance linearised modulators (with linear light-intensity-against-voltage) which will reduce the necessity to use such high optical power.

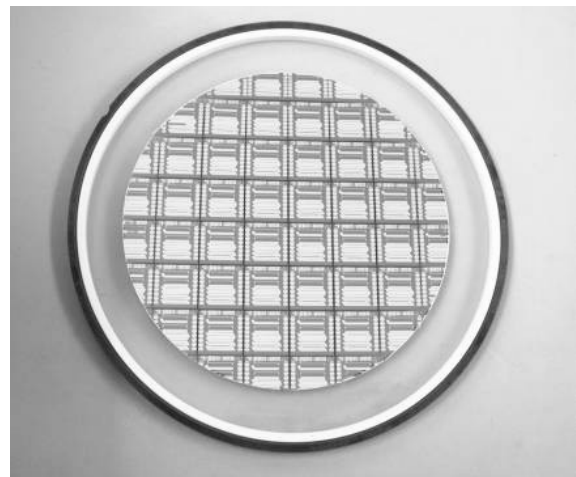


Figure 2. 6-inch (150 mm) diameter GaAs wafer of electro-optic waveguide modulators. The wafer contains 256 modulator die. [RFMD (UK) Ltd.]

In this paper we summarise our programme to develop linearised modulators using a modified version of a high-throughput GaAs p-HEMT fabrication process in a state-of-the-art gallium arsenide fabrication plant. Figure 2 shows a 6-inch (150 mm) diameter GaAs wafer which contains 256 modulator die. Wafers are processed in lots of many wafers at a time. This approach is essential because it allows us to make components with the very high fabrication precision required for controlling the light intensity to the precision necessary for high dynamic range RF-photonic link electrical-

to-optical transducers. In our presentation we will also describe the relevance of these devices to minimising the noise figure (NF) of an RF photonic link.

Y-Fed Directional Coupler

Figure 3 shows a schematic diagram of a Y-fed directional coupler, which has been described in previous EMRS DTC Conference papers [1,2]. It comprises [1,5]: an input fibre and an input guide; a Y-junction splitter; two coupled RF electro-optic guides followed by two coupled DC electro-optic guides with a third central tuning electro-optic guide between them; an output guide and an output fibre.

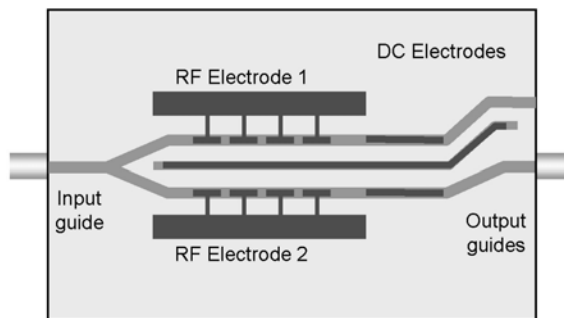


Figure 3. Schematic diagram of an electro-optically tuneable Y-fed directional coupler linearised modulator [1,2,5]. The narrow electro-optic waveguide in the centre of the device is used to control the rate at which light couples between the two wider waveguides.

Briefly, the device works by controlling very accurately the rate at which the light crosses from one electro-optic waveguide to the other by optical coupling (a process equivalent to tunnelling in quantum mechanics). Light which crosses from one guide to the other is electro-optically modulated less strongly than light which passes through the device without coupling. By adding the two different contributions together (the coupled and the non-coupled light) in exactly the correct ratio (R) and phase (ϕ), the output intensity, from the output fibre, can be made to depend linearly on the applied RF voltage. Fortunately ϕ is

set very accurately to the required value (90°) by power conservation in the coupler. However, R is set by the manufacturing parameters (guide width, separation and etch depth) of the two outer electro-optic waveguides. In practice, it is not possible to set these parameters reliably to exactly the correct values, even with a state-of-the-art GaAs process, but it is possible to get close enough to the required value of R and then use the central tuning electrode for very fine control of the coupling rate to give exactly the required ratio.

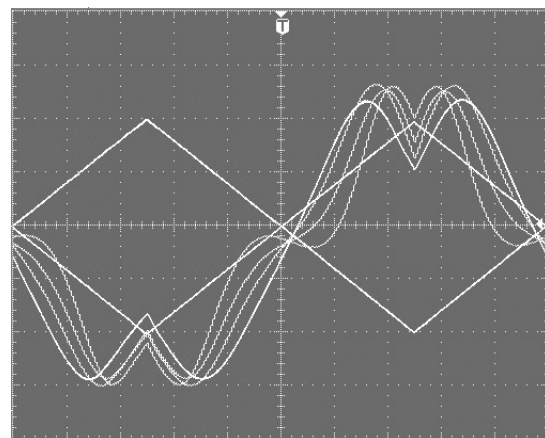


Figure 4. Four measured light-intensity-against-voltage (L-V) responses for a tuneable Y-fed directional coupler modulator [1]. The triangle-wave lines are the voltages applied to the two signal electrodes. The four L-V responses are for the tuning voltages 1) -10.5V, 2) 0V, 3) 20 V and 4) 30V.

The effect of changing the tuning electrode on the light-intensity-against-voltage (L-V) curve is shown in Figure 4 [1]. The tuning voltage changes the ratio R , and for all the L-V curves except the linear one in Figure 4, the coupling rate is not high enough so that too much light is over-modulated. Our most recent measurements of the SFDR of packaged Y-fed directional coupler devices operating in an RF-photonic link are shown in Figure 5b (compared with results for a standard MZ modulator in Figure 5a). The output power in each harmonic is plotted against input RF power (over 12 decades of input power). The MZ L-V response is

sinusoidal rather than linear and is operated around its quadrature point where it behaves as a linear device up to the point where the third harmonic becomes significant. The main aim of linearising a modulator is to reduce the power in the third harmonic, preferably to the level of the fifth harmonic or below.

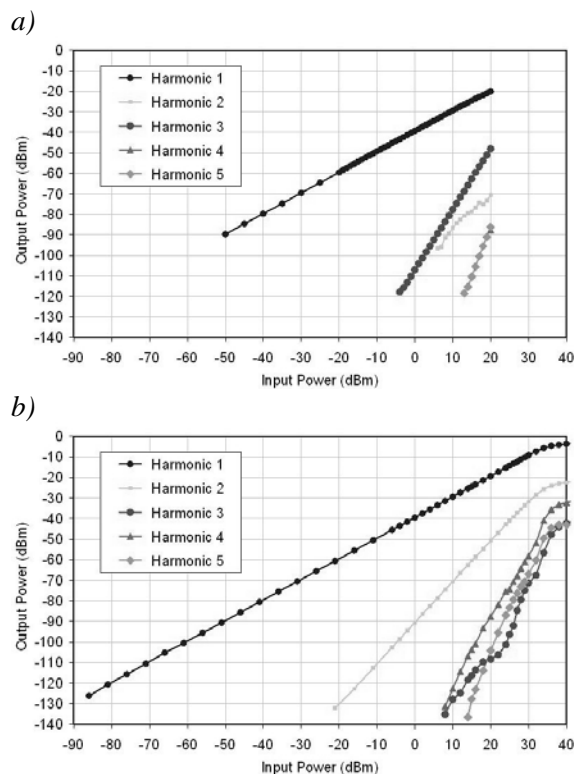


Figure 5. Graph of the measured output power in different harmonics from RF-photonics links with different types of modulator: a) Mach Zehnder; b) Tuneable Y-fed directional coupler.

It can clearly be seen from Figure 5 that the third harmonic has been significantly suppressed and is entirely below the fifth harmonic. For an input power of 10 dBm, for example, the output power in Figure 5a is approximately -80 dBm whereas in Figure 5b it is closer to -130 dBm. This corresponds to an increase in the “third-order-limited” SFDR of 50 dB. For an input power of 20 dBm, the improvement is closer to 60 dB. Note, however, that this improvement is at the expense of increasing the power in the second harmonic (by

approximately 20 dB). For narrow-band applications, spurious signals generated by second and fourth order intermixing (such as second and fourth harmonics) do not appear in the frequency band of interest and so should be less of a concern than spurious signals generated by third and fifth order intermixing. However, it is still a limitation of the current device that the second harmonic increases as the third harmonic is suppressed. One aim of this year’s work has been to investigate the reason for this “crosstalk” between the different harmonics as the device is tuned. The critical point about this result though is that, unlike a conventional MZ modulator in which the third harmonic cannot be changed at all, we have demonstrated a component in which the third harmonic (and all corresponding third order intermixing products) can be minimised (often to a level below the noise floor) by adjusting a single bias voltage. This Y-fed directional coupler device has not just one bias voltage that controls the even harmonics (as in an MZ device), but also an extra bias voltage that controls the odd harmonics. Although, in practice, there is currently some crosstalk between the different bias voltages and the harmonics they control, it is clear from our measurements that the crosstalk can be minimised and it should be possible to minimise both second and third harmonics simultaneously in this type of component.

Although a Y-fed directional coupler device can be used to demonstrate the important step of reducing the third harmonic very significantly below the corresponding level in a conventional “non-linearised” MZ modulator, it potentially has the drawback that for fixed bias voltages, the third harmonic suppression only occurs over a narrow frequency range. We should stress that the exact frequency range has not been measured accurately for our devices and it may be large enough to be useful for certain applications. However, mainly because the RF travelling wave line [1,2] is lossy, it is

likely that this type of device has a limited bandwidth over which the third harmonic can be suppressed with a single set of bias voltages. It will still be possible to tune the device to suppress the third harmonic at other centre frequencies, but it is probably not possible to find a single set of bias voltages that linearise the device over the whole 1 to 20 GHz frequency range.

Four-Guide Mach Zehnder Modulator

To make a broadband linearised modulator [1] we have developed the four-guide Mach Zehnder (MZ) modulator [1]. This device operates in a similar way to the Y-fed directional coupler, by combining two sinusoidal light-against-voltage (L-V) responses, each with a different $V\pi$, with the correct phase difference between them and the correct ratio of optical intensities.

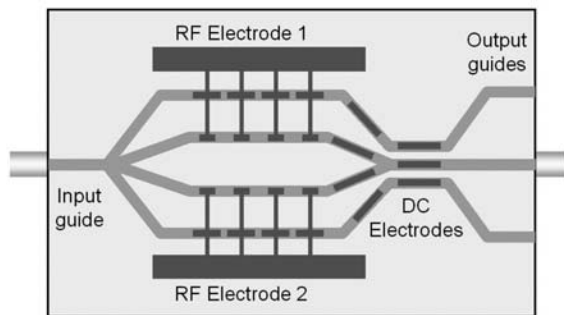


Figure 6. Schematic diagram of a four-guide MZ linearised modulator [1,2,8] – for broadband high SFDR operation.

Figure 6 shows a schematic diagram of a four-guide electro-optic MZ interferometer including the electrode layout and three-guide directional coupler used to control the phase difference and intensity ratio of the different L-V responses. The device comprises an inner and an outer MZ interferometer where the inner one is similar to that of a conventional MZ modulator with a high $V\pi$, and the outer one adds a low $V\pi$ sinusoidal correcting term. A linear L-V response can be achieved by setting both the inner MZ and

the outer MZ to their quadrature points (the linear part between the maximum and minimum intensities), and combining their outputs in a single guide, using the three guide directional coupler. The linearization mechanism is similar to that used in the Y-fed directional coupler device except that it should be independent of the RF frequency.

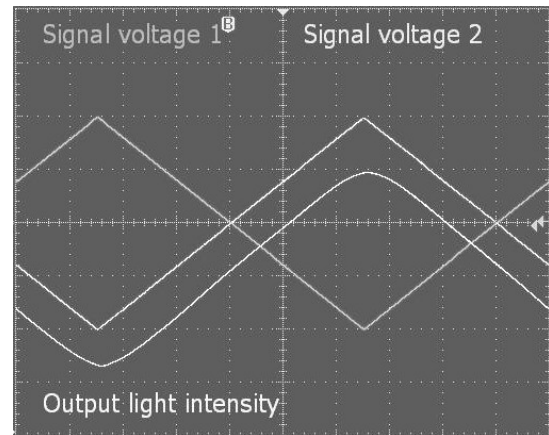


Figure 7. Measured light-intensity-against-voltage (L-V) response of a Four-guide MZ linearised modulator.

Figure 7 shows a low frequency L-V response of a four-guide MZ modulator. There is clearly a linear central part of the L-V curve. However, this device has proved to be more difficult than the Y-fed directional coupler to operate with suppressed third harmonic at higher frequencies. This is because it requires at least four bias voltages to adjust the optical phases of the four electro-optic guides as well as setting the correct intensity ratio using the three-guide directional coupler.

We presented preliminary RF results from four-guide Mach Zehnder modulators at last year's EMRS DTC conference, which showed a small suppression of the third harmonic [1]. However, we now believe that this result was achieved with the device incorrectly biased. Although it should be possible to bias the device to give a more significant reduction of the third harmonic (>10 dB), we have currently been unable to demonstrate this because the low frequency

linearising bias voltages do not correspond to the correct high frequency values. We have developed a modified device with a three guide input coupler to simplify the biasing process for this type of device.

Low voltage linearised modulators.

Because the linearization process involves adding a low $V\pi$ L-V to a high $V\pi$ L-V, the overall effective $V\pi$ is usually at least twice the corresponding value for a conventional non-linearised Mach Zehnder modulator. For this reason, we have developed 40 mm long linearised modulators in addition to our standard 20 mm long devices. We have made 40 mm versions of both tuneable Y-fed directional coupler devices and four-guide Mach Zehnder modulators. The main differences between the 40 mm devices and the 20 mm ones is that they have different coupled guide pitches. Our recent measurements on the 40 mm devices show that they behave in the same way as the 20 mm ones but have $V\pi$ values typically three times smaller than the shorter devices.

Conclusions

In this programme we have concentrated on making broadband linearised (high SFDR) electro-optic waveguide modulators for military RF applications. This is probably one of the most challenging photonic devices for any fabrication technology and it is an indication of the quality of the high-throughput “modified p-HEMT” process we have used that we have been able to demonstrate components with significant linearisation and suppression of the third harmonic. It should be emphasised that the precision with which these devices have been made corresponds to a variation of the critical waveguide parameters (width, height and pitch) of the order of tens of nanometres over device lengths of up to 40 mm. It is this remarkable precision that allows us to make devices that have performances significantly beyond what can

be achieved with other technologies or other (lower volume) fabrication plants.

In this programme we have developed two new device design concepts (both now patented) which are: 1) the tuneable Y-fed directional coupler modulator, and 2) the four-guide Mach Zehnder modulator. At the start of this programme neither of these components would have been thought possible because of the very high precision fabrication process required to make them. We now believe that these devices have not only been successfully demonstrated, but are also manufacturable – which we see as one of the key aims (in terms of “pull-through” to military systems) of the EMRS DTC programme.

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