Development of GaAs Electro-Optic Modulators with Improved Dynamic Range

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Abstract

We describe the design, fabrication, testing and measured performance of linearised GaAs electro-optic waveguide modulators for high dynamic range military RF applications. We demonstrate devices with >10 dB suppression of the third harmonic compared to a conventional Mach Zehnder modulator and describe methods for improving this further.

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

Introduction

The considerable improvements during the past five years of photonic components for digital telecommunications applications has led to a renewed interest in the potential use of photonics for a range of military microwave systems.

These potential RF-photonic applications include the following examples.

1) The use of optical fibre RF-photonic links to transmit broadband microwave signals (such as those encountered in electronic warfare systems) around military platforms with negligible distortion or dispersion.
2) Direct optical sampling and digitisation of broadband microwave signals for electronic surveillance and signals intelligence receivers.
3) Switched RF-photonic delay lines to give true-time-delays for: a) electronic countermeasures (jamming and false target generation), and b) squint-free broadband or multifunction phased array radars.
4) For transmitting or receiving signals from remote antennas or for distributing the local oscillator in conformal phased array radars.

The main reason why RF-photonics is not more widely used for military applications is that it is not currently possible to achieve the high dynamic range required (often over a very wide bandwidth) for most of these operations.

The aim of this programme is to address this limitation directly by developing a linearised electrical-to-optical intensity modulator with a broadband high dynamic range [1-6]. Our target is to achieve a 20 dB improvement in the spurious free dynamic range (SFDR) compared to the electro-optic waveguide Mach Zehnder modulators that are currently used for military RF photonic applications.

We describe the design, fabrication and testing of GaAs Y-fed directional coupler linearised modulators [1,3] with >10 dB suppression of the third harmonic compared to a conventional Mach Zehnder modulator and describe methods for improving this further.

Linearisation of Electro-Optic Waveguide Modulators

The main approach to making a linearised electro-optic waveguide modulator for broadband applications involves making a device in which the light can pass through a set of well defined different optical paths, with different electro-optic phase shifts, and adding the contributions from each path with well defined phases and amplitudes into a single output guide. In one of the simplest cases of a device with four paths, for example, two paths may act as a balanced interferometer with an accurate sinusoidal light-intensity-against-voltage (L-V) response with an on-to-off switching voltage Vπ of say 3V and the other two paths may act in the same way but with a Vπ of 9V. By adding the outputs from these two paths together in the correct amplitude and phase, the Vπ = 9V sinusoidal response is linearised by the addition of the Vπ = 3V response.

Because the phases and amplitudes of the light contributions from the different paths have to be very accurately matched to achieve the high dynamic ranges required by military systems, it is important to: a) use a very precise and repeatable optical waveguide technology, and b) use a device layout that maintains the phase differences (RF and DC) very accurately between the different contributions.

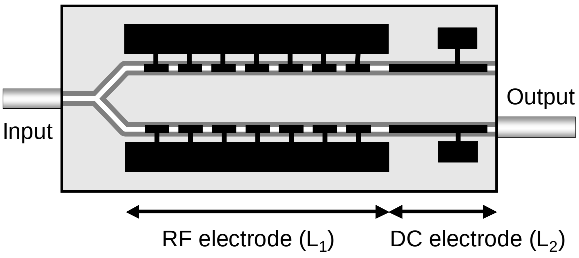

Figure 1. *Schematic diagram of a Y-fed directional coupler linearised modulator.*

The approach that we have used in this paper is to make GaAs electro-optic waveguide linearised modulators using a Y-fed directional coupler layout, as shown schematically in Figure 1. The light enters the input guide and is split symmetrically into two coupled guides by a Y-junction. Each waveguide has two electro-optic electrodes on it: 1) an RF signal electrode and 2) a DC tuning electrode.

This device works by allowing most of the light to couple across from one guide to the other as it propagates under the RF signal electrode. This means that the electro-optic phase shift applied to the light in the first part of this electrode is partially cancelled by the negative phase shift applied to the light in the other guide in the second part. But some light passes straight through the coupler remaining in the same guide throughout. This light sees a stronger electro-optic phase shift because it is always under the same electrode. The coupled waveguides underneath the output DC tuning electrodes are used to add together these two contributions in the correct amplitude and phase.

Low Frequency Test Devices

Low frequency Y-fed directional coupler devices were made using the Filtronic Compound Semiconductor GaAs optical waveguide process [1], which is based on a modified version of the high throughput 6” wafer GaAs p-HEMT process. This is essential for making linearised modulators because the process is well suited to making high performance optical waveguide devices in which the intensities and phases of the different optical paths can be controlled very accurately.

Because the light intensity in the uncoupled (low Vπ) and coupled (high Vπ) paths have to be added in the correct proportions to give a linear L-V response, design calculations were performed to determine the optimum coupled guide parameters to give the correct coupling constant (κ). The lengths L_1 and L_2 of the coupled guides under the RF electrode and the DC electrode respectively were fixed by the lithography to be in the ratio 10 to 6. This ratio does not need to be set particularly accurately because there is a range of combinations of the L_1 / L_2 ratio and the coupling constant κ that give maximum SFDR. However, once this ratio has been fixed, the value of κ needs to be set to its correct value to better than ±0.1% to achieve a 10 dB improvement on the SFDR of a Mach Zehnder modulator.

The coupling constant κ depends on the waveguide width, pitch and etch depth. The width and pitch can be set fairly accurately by the lithography. The etch depth is sufficiently uniform, but the exact target depth is more difficult to achieve in practice with the required precision. For this reason we made a number of devices that were identical except for the guide pitch, which was used partly to explore the behaviour of the devices with a range of different coupling constants, but also to ensure that some devices would be linear even if the target etch depth were not achieved in practice.

These devices were made in the Filtronic GaAs fab and then the cleaved facets were antireflection coated.

Measurements and Results

The devices were measured using a test bench with lensed fibres for launching and receiving the light from a tuneable (1520nm to 1590 nm) laser. Voltages were applied to the pair of signal electrodes as two triangle waves in antiphase. The tuning electrodes initially were not biased.

Figure 2 shows the L-V responses of three different devices together with the drive voltage waveforms as displayed on an oscilloscope. The three devices had guide pitches of a) 10.5 μm, b) 10.3 μm and c) 10.1 μm. They were designed to have an optimum guide pitch of 10.0 μm for the target etch depth. The L-V response shown in Figure 2 a) shows clearly the addition of L-V responses with both low and high Vπ. However, the amount of light in the low Vπ response is too high, which indicates that the coupling constant is too low. There is less power in the low Vπ response in Figure 2 b) and even less in Figure 2 c) which shows the most linear L-V response.

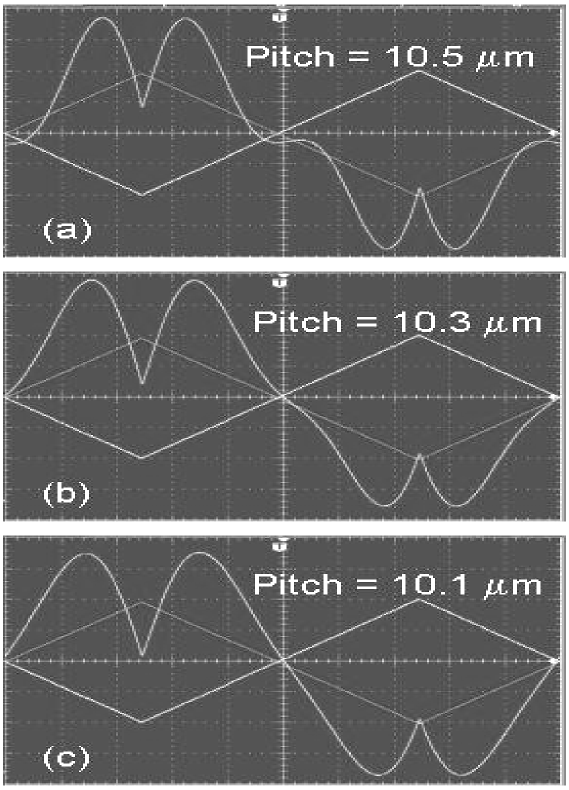

Figure 2. *Three light-intensity-against-voltage responses for Y-fed directional coupler modulators with different guide pitches. The triangle-wave lines are the voltages applied to the two signal electrodes of the Y-fed directional coupler. The design pitch for optimum linearity was 10.0 μm.*

The original idea was that the tuning electrodes would enable the coupling constant to be tuned in the DC part of the device. However, this was found to be a much weaker effect than expected, possibly due to surface conduction effects.

The most linear device was tested using a 10 MHz signal from a synthesizer for different input RF power levels. Figure 3 shows the output RF power levels for the fundamental frequency and the lowest four harmonics plotted against input power. The fundamental frequency is well behaved between –56 dBm input power and +10 dBm. The third harmonic – the one we are trying to minimise by adding the high Vπ response – is clearly suppressed almost to the same level as the fifth harmonic, which indicates that the linearisation method works as planned. However, the second harmonic is higher than it should be. In fact, for a completely symmetric device, the second harmonic should not be seen at all.

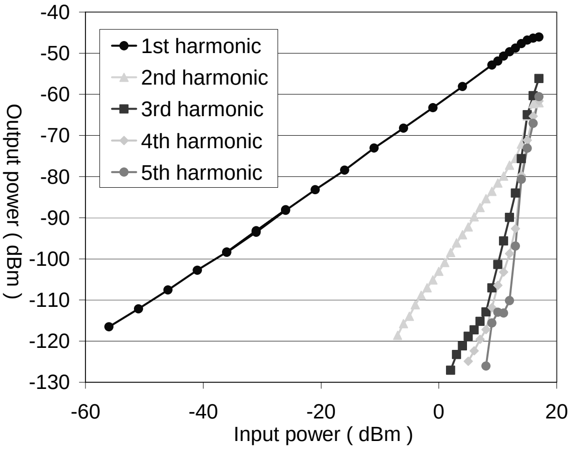

Figure 3. *Graph of the output power in different harmonics from an RF-photonic link. This graph is used to determine the spurious free dynamic range (SFDR) of the linearised modulator. Note that the optical power incident on the device was ~ 0 dBm (optical) – increasing this to say 15 dBm (optical) (a more practical value) would move all of these curves up by 30 dB (electrical).*

The second harmonic can be reduced by adjusting the bias voltages on the signal and tuning electrodes to some extent, but there is a subtle reason related to the quadratic electro-optic effect and the single-sided bias method (rather than push-pull) used in this test that means that the devices are not completely symmetrically driven at low frequencies and so will show some second harmonic at 10 MHz but not at typical military RF frequencies.

Table 1 shows how the results in Figure 3 compare with corresponding results for a Mach Zehnder device. A good way to compare these results directly is to measure the SFDR at output power levels that are a certain number of dB below the output power peak. This takes into account that the devices may have different optical losses. Neglecting the second harmonics (which is a reasonable thing to do at low frequencies), the SFDR of the linearised modulator is between 10 and 16 dB better than that of a Mach Zehnder modulator.

SFDR Comparison Table	Non-linearized Mach Zehnder modulator	Linearised Y-fed directional coupler modulator
5 dB below output peak	35 dB	45 dB [30 dB]
10 dB below output peak	44 dB	60 dB [33 dB]
15 dB below output peak	55 dB	68 dB [38 dB]
20 dB below output peak	(62 dB)	(77 dB) [44 dB]

Table 1. *Spurious free dynamic range (SFDR) comparison table – neglecting the second harmonic. The numbers in round brackets are extrapolated from the measured results. The numbers in square brackets include the second harmonic.*

Narrowband and Broadband RF Devices

Having demonstrated low frequency test devices, we have recently fabricated some RF Y-fed directional coupler devices (as well as some low-frequency test devices with an improved tuning mechanism). The RF devices have not been tested for their bandwidth at the time of writing, but it is expected that the bandwidth will not be the full 1 to 20 GHz because of the nature of the Y-fed directional coupler design. This is because the electro-optic phase modulation occurs at the same time as the separation of the light between the low and high Vπ paths. The RF loss on the travelling wave CPS transmission line will affect the strength of the electro-optic phase shift, as well as changing the intensity split ratio between the different optical paths.

There are ways to avoid this, for example by using the device layout shown schematically in Figure 4.

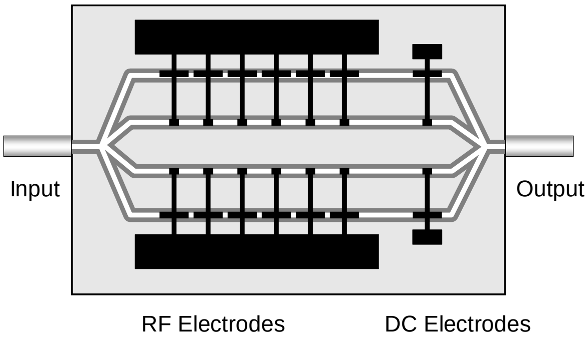

Figure 4. *Schematic diagram of a Four guide Mach Zehnder linearised modulator – for broadband high SFDR operation.*

In this four guide Mach Zehnder modulator, the four different paths are more easily recognised than in a Y-fed directional coupler. The splitting and recombination of the different paths is also separate from the electro-optic phase shifts and so will be independent of the RF loss on the travelling wave transmission line.

Conclusions and Future Work

We have demonstrated a passively linearised modulator (without active tuning of the linearisation mechanism) with an SFDR >10 dBm higher than that of a conventional Mach Zehnder modulator (neglecting the second harmonic). One of the main conclusions from this work is that tuning (and subsequent stabilisation) is essential for practical linearised devices.

To achieve the high SFDR required for military systems, the intensities and phases must be maintained to their correct values very accurately. The precision required cannot currently be achieved in any waveguide technology to make a purely passively linearised modulator. There will always be one critical fabrication parameter that cannot be realised with sufficient accuracy. However, with electro-optic tuning we should be able to: 1) reduce the device sensitivity to etch depth, and 2) improve the SFDR further compared to that of a Mach Zehnder modulator. Our initial tests on a new tuning method for a Y-fed directional coupler device look promising.

We have analysed a wide range of different linearised modulator designs and concluded that these all operate on a very similar principle. However, some are likely to operate over a broader bandwidth than others. In the next phase of this programme we plan to explore the bandwidth of the Y-fed directional coupler devices as well as the four-guide Mach Zehnder device, which is expected to have a high SFDR over the full 1 to 20 GHz frequency range.

We also plan to demonstrate a broadband stabilised high SFDR RF-photonic link using fully packaged devices with the most suitable linearised modulator design.

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