NORMAL-INCIDENCE 1.56-μm MQW ASYMMETRIC FABRY-PEROT MODULATOR (AFPM) FOR PASSIVE PICOCELLS

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Abstract: We have fabricated air-bridged modulators with bandwidths exceeding 10-GHz, the highest yet reported for InGaAsP/InGaAsP MQW AFPMs. Third-order intermodulation between the photodetected downlink signal and the modulated uplink signal is characterised for the first time.

Introduction

Electroabsorption modulators (EAMs) based on the quantum-confined Stark effect (QCSE) will play an important role in future Passive Picocell applications [1][2] as a simple low-cost electrical/optical transceiver. In this respect, the asymmetric Fabry-Perot modulator (AFPM) possesses a number of advantages over waveguide type EAMs. Being a vertically addressed optical intensity modulator, the AFPM is inherently insensitive to the light polarization since the electric field of the input optical signal is always in the plane of the absorbing quantum well layers, thus avoiding the need for active polarisation control. Optical insertion loss is also small because of a relatively large (~20 μm diameter) optical window compared to the typical small waveguide cross-sectional area of 1 μm × 0.26 μm of an InGaAsP/InGaAsP MQW EAM [3]. Previously, we reported a substrate-addressed AFPM with a bandwidth of 3.7 GHz, limited by its large mesa diameter of 100 μm required for wire bonding [2]. We have since designed and fabricated top-addressed air-bridged AFPMs in which the contact pads are remotely located, allowing the mesa diameter to decrease to ~35 μm and achieving a bandwidth exceeding 10 GHz. In this paper, we present results for this new air-bridged AFPM, including the first report of the third-order intermodulation characteristics between the photodetected downlink signal and the modulated uplink signal when the device is used as a photodetector and modulator simultaneously.

Device structure

The layer structure for the fabrication of the AFPM was grown by MOCVD on a semi-insulating InP substrate and consisted of (from the top of the grown wafer) a p-doped top distributed Bragg reflector (DBR), an undoped intrinsic 30-period MQW absorbing region and an n-doped bottom DBR, as illustrated in Figure 1. All layers are lattice-matched to the InP substrate.

![AFM layer structure](image)

In Figure 1, the MQW region, which has a peak exciton absorption wavelength around 1530 nm, is positioned within an asymmetric cavity formed between the highly reflective (91%) bottom DBR and a partially reflective (34%) top mirror consisting of the air-InGaAsP interface and the top DBR. The cavity length is such that destructive interference occurs at the operating wavelength between the light reflected from the top mirror and that from the bottom DBR.

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The wafer was then processed into high-speed air-bridged AFPMs using a novel technique we developed, involving only two metallisation and three wet etching steps. Figure 2 and Figure 3 illustrate the AFPM structure.

![Schematic cross-section of the air-bridged AFPM](image1)

**Figure 2:** Schematic cross-section of the air-bridged AFPM.

![Top microscopic view of a fabricated air-bridged AFPM](image2)

**Figure 3:** Top microscopic view of a fabricated air-bridged AFPM.

The metal system used for the p-layer contact pad, the 5 µm wide air-bridges and the ring on the AFPM mesa was 20nm/250nm Cr/Au while 20nm/300nm GeAu/Au was used for the n-layer contact pad. Because of the small optical window (20 µm in diameter), two slots were included in the ring design in order to aid the metal lift-off during fabrication.

**Experimental results**

For measurements, the AFPM was mounted on a brass block. The n-layer contact pad was connected with silver epoxy to the brass block, which acted as the signal ground. Aluminium wires were used to connect the p-layer contact pad to the centre of a 2 cm long 50 Ω characteristic impedance microstrip transmission line. SMA connectors were then attached to both ends of the microstrip line with one end terminated in a 50 Ω resistor through a blocking capacitor while the other connected to a microwave signal source through a bias-tee. All modulation and photodetection measurements were performed with free-space optics.

Optical reflectance and photocurrent were first measured in order to locate the operating wavelength for the AFPM at which destructive interference occurs. Figure 4 shows the photocurrent and optical reflectance spectra and it can be seen that destructive interference occurs at 1560 nm wavelength. The position of the photocurrent peak did not coincide with the dip in the optical reflectance spectrum because the MQW exciton absorption peak was at 1530 nm.

![Optical reflectance and photocurrent vs. wavelength](image3)

**Figure 4:** Optical reflectance and photocurrent vs. wavelength. Incident optical power was 68.1 µW and the AFPM was biased at 0 V.

After selecting 1560 nm as the operating wavelength, bias dependent photocurrent and optical reflectance measurements were then carried out to establish the optimum bias voltage for maximum modulation efficiency. Figure 5 shows the measured results.

![Optical reflectance and photocurrent vs. reverse bias](image4)

**Figure 5:** Optical reflectance and photocurrent vs. reverse bias. Wavelength and incident optical power were 1560 nm and 68.1 µW, respectively.

At a reverse bias of 2 V, the AFPM shows a maximum –dr/dV of 6.24%/V, where dr is the incremental change in optical reflectance and dV the incremental change in terminal voltage. Also from Figure 5 the optical insertion loss is calculated to be 4.2 dB at 0 V.
The modulation frequency response was measured with a Rohde & Schwarz SMP04 microwave signal source driving the AFPM and an HP71400C lightwave signal analyser (LSA) detecting the AFPM modulated optical signal. The modulation frequency response shown in Figure 6 is relative to that of the AFPM at 1 GHz at which a 9.6% optical modulation depth was measured with a +6 dBm electrical modulation signal power.

The AFPM shows an electrical –3-dB bandwidth of just over 10 GHz which, to the authors’ knowledge, is the highest yet reported for an InGaAsP/InGaAsP MQW based AFPM. It is also worth noting that for narrowband operations, the AFPM is still useable up to 18 GHz beyond which the frequency response starts to roll off steeply. The AFPM had a capacitance of 260 fF at 2V reverse bias. We calculated that if the AFPM frequency response had been limited by this capacitance and the transmission line characteristic impedance, the −3-dB bandwidth would have been over 24 GHz. We suspect that the AFPM high-frequency performance is at the moment limited by a combination of the electrical package, the aluminium bond wires and the device series resistance which we will investigate further. Barron et al [4] on the other hand reported 37 GHz bandwidth of their AFPMs using 80 GaAs/AlGaAs MQWs with a device capacitance of 21 fF.

We performed two-tone third-order intermodulation measurements. The two test tones, at 6 GHz and 6.000 010 GHz, were provided by two Rohde & Schwarz SMP04 microwave sources, and then combined and delivered to the AFPM. To measure the weak third-order distortion products in the modulated optical signal, the light reflected from the AFPM was optically amplified with an EDFA before being measured with an LSA. The fundamental signals and third-order distortion products were measured by varying the input power levels of the two tones. The results are shown in Figure 7.

The LSA had an optical responsivity of 0.81A/W at its optical input and detected an averaged optical power of 2.34 mW. With this information, the shot noise was calculated to be –165 dBm (1 Hz) which is 9 dB higher than the thermal noise limit of –174 dBm (1 Hz). The shot noise limit is therefore used as the noise floor in Figure 7 and the spurious free dynamic range (SFDR) was found to be 87 dB (1 Hz).

The EDFA was biased to provide an optical gain of 22 dB. However the results shown in Figure 7 also included losses due to coupling of the AFPM reflected light into a fibre, and the beam splitter which was used to separate the light incident on and reflected from the AFPM. These two losses are estimated to be 6.2 dB and 3.1 dB, respectively.

The AFPM has been designed to work simultaneously as an optical intensity modulator and a photodetector for passive picocell applications. In such applications, the AFPM photodetects the optical downlink signal from a central station and at the same time uses the applied electrical uplink signal to modulate and reflect the residual light left over from the downlink direction back to the central station. There have been numerous reports on the intermodulation characteristics of electroabsorption modulators solely as a modulator, e.g. [5]. In passive picocell applications, both downlink and uplink signals are present on an AFPM, but to date there has been no detailed report on the third-order intermodulation between these two signals which is important for sub-octave operations.

To characterise downlink/uplink intermodulation, we employed a separate electroabsorption modulator [3] to generate an intensity modulated downlink signal. The downlink signal was then optically amplified by an
EDFA before being photodetected by the AFPM. Simultaneously, the AFPM was driven by an electrical uplink signal. Intermodulation present in the AFPM reflected light was then measured with the LSA as a function of the average incident optical power controlled by varying the bias current of the EDFA.

Figure 8 shows the presence of the third-order intermodulation products at 40 dB and 44 dB below the uplink signal in the detected spectrum of the AFPM reflected light. Figure 9 plots how these two intermodulation products and two fundamental uplink and residual downlink signals varied with the mean incident optical power. It can be seen that the detected residual downlink signal increased correspondingly with the mean incident optical power. However, the detected AFPM modulated uplink signal increased by only 2 dB (elec.) for 5.6 dB increase in the optical power, suggesting that the AFPM was saturated by the strong incident light. The two intermodulation products were also seen to increase with the mean incident optical power.

To improve the frequency response further, inclusion of a top InGaAs cap layer on future wafers for reducing p-layer contact series resistance will be considered. To improve the modulation depth, the number of quantum wells used might need to be doubled. Use of an InGaAs/AlInGaAs MQW region, which has shown more pronounced exciton absorption, will also be investigated. Finally, for enhanced SFDR we will look at a number of design and operating variables of the AFPM, including the thickness of the MQW absorbing region and the front mirror reflectance as well as the bias voltage and examine how the SFDR is affected by them.

Conclusion

We have designed and fabricated air-bridged AFPMs based on InGaAsP/InGaAsP MQWs. The ~3-dB (electrical) modulation bandwidth exceeds 10 GHz and the AFPM is still useable up to 18 GHz. SFDR measured is 87 dB (1 Hz). For the first time, results of the third-order intermodulation between the photodetected downlink signal and the modulated uplink signal have also been presented.

References