Multiple Quantum Well
Asymmetric Fabry-Perot Modulator/Detector for GANDALF Radio-Over-Fibre Applications

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Abstract — This paper describes the design and characteristics of a 15 GHz air-bridged InGaAsP/InGaAsP
Multiple Quantum Well (MQW) Asymmetric Fabry-Perot Modulator/Detector (AFPM). The AFPM is light
polarisation insensitive and has been packaged and integrated in a GANDALF Base Station, functioning
simultaneously as an optical modulator and a photodetector.

Index Terms — Asymmetric Fabry-Perot Modulator/Detector (AFPM), Electroabsorption Modulator
(EAM), Multiple Quantum Well (MQW), Radio-over-Fibre, GANDALF.

I. INTRODUCTION

In the GANDALF project [1], one of the access scenarios is the simultaneous provision of both wireline
Data Over Cable Service Interface Specification (DOCSIS) and wireless DOCSIS broadband services
over a fibre optic link. In this respect, it has been decided to investigate using a Quantum-confined Stark
effect (QCSE) electroabsorption modulator/detectors (EAMs) as a simple low-cost electrical/optical
transceiver [2][3] in a Base Station (BS). In particular, the normal-incidence asymmetric Fabry-Perot
modulator/detector (AFPM) possesses a number of advantages over the waveguide type EAM, including
polarisation insensitivity and low optical insertion loss due to a large (~20µm diameter) optical window
compared to the small cross-sectional area of the waveguide EAM. Previously, we reported a 10GHz
InGaAsP/InGaAsP multiple quantum well (MQW) AFPM and performed static and microwave
characterisations, bi-directional broadband wireless over fibre transmissions with the AFPM functioning as both
an optical modulator and a photodetector, and the first direct integration with a microstrip patch antenna for
operation at 5.2GHz [4]. We have since modified the device epitaxial design by incorporating a highly p-doped
InGaAs cap layer for low contact resistance. The mask design has also been enhanced with a novel feature which
will allow AFPMs with the required resonance wavelength to be selected using a simple and efficient
reflection microscope arrangement before the expensive and time-consuming cleaving and packaging processes.
One such new AFPM has been packaged and integrated in the GANDALF DOCSIS/wDOCSIS BS and full-
duplex signal transmissions have been demonstrated and results published in due course. In this paper we report
on design and characteristics of this new AFPM behind the Gandalf BS.

II. DEVICE STRUCTURE

The AFPM layer structure shown in Fig. 1 was grown by MOVPE on a semi-insulating InP substrate and consisted (from the top of the grown wafer) of a highly p-doped InGaAs cap layer, a p-doped 2-period top DBR,
an intrinsic 30-period InGaAsP/InGaAsP MQW absorbing region and finally an n-doped 20-period
bottom DBR. All layers were lattice matched to the InP substrate. The excitonic absorption peak of the MQW
region is at a wavelength of approximately 1520nm at 0V bias. The top InGaAs cap layer is used only for low
resistance metallisation and so is not part of the AFPM optical structure. This InGaAs layer was etched away
from the optical window during device fabrication.
The asymmetric Fabry-Perot cavity is formed between the highly reflective (91%) bottom DBR and a partially reflective (35%) top mirror consisting of the air-InP interface and the top DBR. The cavity length is such that destructive interference occurs at the resonance or operating wavelength between the light reflected from the top mirror and that from the bottom DBR.

The wafer was processed into air-bridged AFPMs with mesa diameter around 35 µm. Fig. 2 shows the AFPM schematic cross-section while Fig. 3 shows a top microscopic photo of the device.

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 after the p-layer contact metallisation.

Being a Fabry-Perot cavity structure, the AFPM resonance wavelength is sensitive to the epitaxial layer thicknesses and varies across a typical two-inch MOVPE grown wafer from which devices are fabricated. It is therefore important to be able to measure and select readily AFPMs with the correct resonance wavelength before the expensive and time-consuming cleaving and packaging processes. Two large (50 µm diameter) pads, having the same layer structure as the AFPM mesa within the optical window, have therefore been included in the design and can be optically assessed in order to determine their respective resonance wavelengths with an optical spectrum analyser and a simple reflection microscope arrangement whose light spot size is, however, too large for assessing the 20 µm AFPM optical window directly. Therefore the resonance wavelength of the AFPM mesa itself can be deduced by interpolating those of the two neighbouring 50 µm pads. The AFPM selected for use in this work has resonance wavelength at 1557 nm.

III. EXPERIMENTAL RESULTS

The selected AFPM was cleaved and 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. Silver epoxy was also used to connect the p-layer contact pad to the centre of a 2 cm long 50 Ω characteristic impedance microstrip transmission line with SMA connectors at both ends. One of the SMA connectors was terminated in a 50 Ω resistor through a DC blocking capacitor while the other connected to a microwave signal source through a bias-tee.

Since both the unmodulated light is incident on and the modulated light is reflected from the AFPM through the single optical window, a lensed fibre and an optical circulator were used to couple and separate these two
optical signals. Fig. 4 shows the reflected optical power spectrum, including the 2dB optical circulator loss, as the input tuneable laser wavelength was varied from 1470nm to 1584nm.

Variations of the reflected optical power and photocurrent with the reverse bias voltage at the AFPM resonance wavelength of 1557nm were measured and the results are shown in Fig. 5.

At 0V bias, the optical insertion loss is 7dB including the 2dB loss of the circulator used. At 3.4V bias, the modulation slope, -dR/dV, is 3.2%/V, where dR is the incremental change in optical reflectance and dV the incremental change in terminal voltage, and the responsivity is 0.28A/W. The reflectance contrast ratio is about 2dB.

The modulation frequency response scaled relative to that of the AFPM at 1GHz is shown in Fig. 6.

The ripples seen in Fig. 6 are due to the microwave test package used. The device -3dB electrical modulation bandwidth exceeds 15GHz which to the authors’ knowledge is the highest reported for an InGaAsP/InGaAsP MQW AFPM. In other material systems, Barron et al [5] reported 37GHz bandwidth for their 80-period GaAs/AlGaAs MQW AFPM at 864nm wavelength while Huang et al [6] reported 20GHz bandwidth for their 50-period InGaAs/InAlAs MQW AFPM at 1.55µm wavelength.

The dependence of the AFPM modulated output power on the input laser wavelength was investigated. The AFPM was modulated at 10GHz while the input CW laser wavelength was tuned from 1470nm to 1584nm. A lightwave signal analyser (LSA) with an input responsivity of 0.81A/W was used to detect the AFPM output modulated optical power and the results are shown in Fig. 7 at four incident optical power levels.
Peak AFPM modulated powers were detected between 1560.5nm and 1563.5nm, depending on the incident optical power. The optical bandwidths, defined as the wavelength range within which the detected AFPM modulated power is within -3dB (elec.) of the peak detected power value, are 18, 17.5, 18 and 19nm at input optical powers of -6, -3, 0 and +3dBm, respectively. Such wide AFPM optical bandwidths can therefore relax the light source wavelength stability requirement and allow the use of low-cost uncooled CWDM lasers.

It is also observed in Fig. 7 that the detected modulated signals at 10GHz exhibit minima between 1533nm and 1535nm. These minima can be explained by noting that if the input laser wavelength coincides with that of the underlying MQW excitonic absorption peak at a given reserve bias voltage, the AFPM modulation slope – dR/dV will be zero and detected modulated output power at the fundamental frequency of 10GHz will also be minimum. To substantiate this explanation for the observed minima, we recall a QCSE rule that the wavelength of the excitonic peak red-shifts with increasing electric field strength in the MQW. The measurements of the detected AFPM modulated power at 10GHz were repeated at four different reverse bias voltages at a fixed incident optical power of -6dBm and the results are shown in Fig. 8.

It can be seen in Fig. 8 that the observed minima do indeed red-shift with increasing reverse bias voltage with an average shift of about 4.3nm/V and the explanation given above for the observed minima in the detected modulated signal power is thus supported.

The results presented so far were obtained with an unpackaged AFPM. A number of AFPMs have now been packaged in modules as shown in Fig. 9 which provide high-speed electrical and FC/PC connectorised optical connections to the AFPM.

IV. CONCLUSIONS

We have fabricated air-bridged modulator/detectors with modulation bandwidths exceeding 15GHz, the highest yet reported for InGaAsP/InGaAsP MQW AFPMs. The variation in the AFPM modulated output power at microwave frequencies with input laser wavelength is shown to be less than 3dB over greater than 17nm, making the devices compatible with low-cost CWDM technology. One AFPM has been packaged and integrated in a Gandalf BS functioning simultaneously as an optical modulator and a photodetector.

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