Design, Fabrication and Characterisation of Normal-Incidence 1.56-µm Multiple-Quantum-Well Asymmetric Fabry-Perot Modulators for Passive Picocells

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SUMMARY We have designed and fabricated air-bridged modulators with bandwidths exceeding 10GHz, the highest yet realised to date for InGaAsP/InGaAsP multiple-quantum-well (MQW) asymmetric Fabry-Perot modulators (AFPMs). Microwave modulation, measurements of intermodulation between the photodetected downlink and modulated uplink signals, and bi-directional broadband data over fibre transmission experiments have been performed to verify the potential of the AFPM as a single electrical/optical transceiver. We also report the first direct integration of this AFPM with a microstrip patch antenna and present results of a preliminary microwave signal transmission experiment over a distance of 1.4m in free-space at 5.2GHz with the integrated AFPM as a photodetector.

key words: AFPM, MQW optical modulator, microwave photonics, fibre radio

1. Introduction

Future broadband wireless networks will operate at microwave frequencies which cannot efficiently be distributed within buildings and the urban environment using conventional microwave cables due to their higher loss. The passive integrated picocell (PIP) concept distributes these signals through optical fibre as microwave modulated optical signals, with a combined modulator/photodetector at each base station to provide a transceiver radio path. In such radio-over-fibre systems, the data rate is usually limited to a few tens of Mbit/s, because of the limited radio spectrum allocated for such data transmission. Invariably, the baseband digital data is up-converted to or encoded on a higher frequency carrier for wireless radio transmission.

For example, in the IEEE 802.11a [1] and the European HYPERLAN/2 [2] standards which are aimed at the wireless local area network (LAN) applications, the maximum data rate is 54 Mbit/s modulated on an RF carrier in the 5GHz band.

Electroabsorption modulators (EAMs) based on the quantum-confined Stark effect (QCSE) are capable of optical modulation as well as photodetection, and will therefore play an important role in future PIP applications [3], [4] 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 polarisation 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 and fibre alignment is easier because of a relatively large (~20 µm diameter) optical window compared to the typically small cross-sectional area of 1 µm × 0.26 µm of a waveguide InGaAsP/InGaAsP MQW EAM [5]. Previously, we reported a substrate-addressed AFPM with a bandwidth of 3.7GHz, limited by its large mesa diameter of 100 µm required for wire bonding [4]. 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 10GHz. In this paper, we present results for this new air-bridged AFPM, including its fabrication procedure, microwave modulation and intermodulation characteristics, bi-directional broadband DPSK 5.2GHz signal transmission experiment over 12.6km fibre and the first direct integration with a microstrip patch antenna.

2. AFPM Structure and Fabrication Procedures

The layer structure for the fabrication of the AFPM was grown by MOVPE on a semi-insulating InP substrate
The wafer sample was first patterned using Fig. 2 showing various parts of a complete device. The cavity length was 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.

The procedure for fabricating AFPMs consisted of four key steps and is described below, with the help of Fig. 2 showing various parts of a complete device.

**Step 1** The wafer sample was first patterned using standard photolithography, followed immediately by evaporation of 20 nm Cr and 250 nm Au. Excess metal was then lifted off with acetone, leaving only those metals for the p-layer contact pad, the 20 µm mesa ring and the 5 µm wide air-bridges. The mesa ring design incorporated two slots which helped remove the metal inside the mesa ring covering the small optical window along with other unwanted metal during the lift-off process.

**Step 2** The area for the n-layer contact pad was patterned and then etched down to the bottom DBR level. 20 nm GeAu and 300 nm Au were then evaporated onto the wafer sample to metallise the n-layer contact pad. Another lift-off process was performed to remove the excess metal.

**Step 3** The area identified by Step 3 in Fig. 2 was etched down to the same bottom DBR level and this step opened up part of the AFPM mesa side-wall.

**Step 4** The two contact pads, the air-bridges and the AFPM mesa were now protected with resist and a long deep etch was carried out. This etching step opened up the remaining mesa sidewall, electrically isolated individual AFPMs and finally formed the air-bridges by undercutting the wafer material beneath them. The etching continued until the material beneath the air-bridges was completely cleared and the semi-insulating substrate reached.

The AFPM layer structure contained both InP and InGaAsP, and therefore the non-selective Adachi etchant HBr:CH₃COOH:K₂Cr₂O₇(1:1:1) was used in Steps 2, 3 and 4. It is well known that the Adachi etchant attacks most gold-based contacts. We have experimented with both Ti/Au and Au/Zn/Au systems for the p-layer metal and found that although the air-bridges were protected with resist, the Adachi etchant would attack from the sides and destroy them. Cr/Au, however, is the only metal system we have found so far which is not attacked by the Adachi etchant and was

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**Fig. 1** AFPM layer structure. λₕ denotes the absorption edge wavelength of the corresponding layer.

**Fig. 2** Top microscopic view of an entire air-bridged AFPM illustrating the fabrication procedures.

**Fig. 3** Schematic cross-section of the air-bridged AFPM.
used in our AFPM fabrication.

Figure 3 and Fig. 4 show the schematic and close-up image of a completed AFPM.

3. AFPM Packaging and Static Characterisation

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 5 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.

After selecting 1560 nm as the operating wavelength, bias dependent photocurrent and optical reflectance measurements were carried out to establish the optimum bias voltage for maximum modulation sensitivity. Figure 6 shows the measured results.

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 Fig. 6 the optical insertion loss is calculated to be 4.2 dB at 0 V.

4. Microwave Modulation and Intermodulation Characteristics

The modulation frequency response was measured with a Rohde & Schwarz SMP04 microwave signal source driving the AFPM and an Agilent 71400C lightwave signal analyser (LSA) detecting the AFPM modulated optical signal. The modulation frequency response shown in Fig. 7 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 for an InGaAsP/InGaAsP MQW based AFPM reported to date. It is also worth noting that for narrowband operations, the AFPM is still usable up to 18 GHz beyond which the frequency response starts to
roll off steeply. The AFPM had a capacitance of 260 fF at 2 V reverse bias. We calculated that if the AFPM frequency response had been limited by this capacitance and the terminated transmission line 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. [7] 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 Fig. 8.

The LSA had an optical responsivity of 0.81 A/W at its optical input and detected an averaged optical power of 1.1 mW. With this information, the shot noise was calculated to be −169 dBm (1 Hz) which is 5 dB higher than the thermal noise limit of −174 dBm (1 Hz). The shot noise limit is therefore used as the noise floor in Fig. 8 and the spurious free dynamic range (SFDR) was found to be 97 dB (1 Hz).

The EDFA was biased to provide an optical gain of 19 dB. However the results shown in Fig. 8 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. [8]. 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.

To characterise downlink/uplink intermodulation, we employed a separate electroabsorption modulator [5] 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 9 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 10 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...
We performed broadband data transmission over fibre with a power.

The two intermodulation products were calculated uplink signal and the two third-order intermodulation products with mean incident optical power. Centre frequency (CF) − 

Fig. 9 Detected spectrum of AFPM reflected light showing intermodulation between downlink and uplink signals. −6.8 dBm mean optical power with 56% modulation depth at 6 GHz incident on AFPM on the downlink path. On the uplink path, the AFPM was driven with a +10 dBm signal at 6.000 010 GHz with 2 V reverse bias.

Fig. 10 Variation of residual downlink signal, AFPM modulated uplink signal and the two third-order intermodulation products with mean incident optical power. Centre frequency (CF) = 6.000 005 GHz.

(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.

5. Bi-Directional Broadband DPSK 5.2 GHz Signal over Fibre Transmission Experiment

We performed broadband data transmission over fibre in the 5 GHz band using the AFPM alternately as a modulator and a photodetector. Figure 11 shows the uplink transmission setup with the AFPM operating as an optical modulator.

A 68 Mbit/s 223 − 1 PRBS was first differentially encoded with a custom-designed circuit built using emitter coupled logic (ECL) gates. The resulting baseband DPSK signal was then used to switch the phase of a 5.189 GHz RF carrier in a double-balanced mixer. Electrical amplification was provided to compensate for the loss during the up-conversion process in the doubled-balanced mixer, and this amplified DPSK signal then drove the AFPM. A non-polarisation sensitive beam splitter cube was used to separate the 1.56 µm wavelength incident CW light and the modulated light reflected by the AFPM before being coupled into a 12.6 km SSM fibre.

After transmission over the fibre, the light was first optically amplified with an EDFA, photodetected with a photodiode and then further amplified. Demodulation of the DPSK signal was then performed directly on the switched 5.189 GHz carrier using a delay line and a double-balanced mixer. One path was delayed by one bit period τ which is equal to (68 Mbit/s)−1 or 14.7 ns. The two paths were then recombined in a double-balanced mixer to recover the data. The recovered data was low-pass filtered with a 2nd order filter of −3 dB bandwidth 200 MHz before being fed to the BER detector and digital oscilloscope for eye diagram monitoring.

Figure 12 shows the measured uplink bit-error-rate (BER) as a function of the 5.189 GHz RF source power and it can be seen that error-free transmission (BER<10−9) was achieved when an RF power of −14.2 dBm or higher was applied. The inset within Fig. 12 shows the clear eye diagram of the recovered 68 Mbit/s 223 − 1 PRBS measured using 0 dBm RF power.

A similar setup for the transmission experiment with the AFPM operated as a photodetector is shown in...
The inset within Fig. 14 shows a clear eye diagram of the recovered 68 Mbit/s 2^{23} – 1 PRBS when 0 dBm RF power was used. 0.14 mW mean optical power was incident on the AFPM. When the RF power used was 0 dBm, error-free transmission was obtained easily, the AFPM was mounted on the ground plane of the antenna as illustrated in Fig. 15. The AFPM n-layer contact pad was connected to the antenna ground and allow the light to be incident on the optical window.

The challenge was how the AFPM should be mounted on the antenna to maximise the radiation efficiency and vent obstructing the radiation pattern of the antenna. To provide the necessary DC bias to the AFPM, a radio-over-fibre and free-space wireless link. In the downlink direction of this configuration, the AFPM photodetects the optical signal from a central site and radiates it through the antenna to a mobile terminal, such as a lap-top computer. In the uplink direction, the antenna picks up the radio signal from a mobile terminal, and uses it to drive the AFPM. The AFPM in turn modulates and reflects the optical signal back to the central site over fibre.

As a first step towards realising such a base station module, we have designed and fabricated a microstrip patch antenna operating at 5.2 GHz, and integrated it with one of the AFPMs functioning as a photodetector. The challenge was how the AFPM should be mounted on the antenna to maximise the radiation efficiency and to provide the necessary DC bias to the AFPM. To prevent obstructions to the radiation pattern of the antenna and allow the light to be incident on the optical window easily, the AFPM was mounted on the ground plane of the antenna as illustrated in Fig. 15. The AFPM n-layer contact pad was connected to the antenna ground.

In both uplink and downlink experiments, the AFPM reverse bias voltage and the average incident optical power were kept at 2 V and 0.14 mW, respectively, which produced a photocurrent of 63 µA. These consistent operating conditions suggest that our AFPM can be used successfully as an electrical/optical transceiver in a full-duplex, radio-over-fibre Picocell environment.

6. Integration with a Microstrip Patch Antenna

The ultimate aim of this work is to produce a very simple base station module consisting of an AFPM directly integrated with a microstrip patch antenna, forming a radio-over-fibre and free-space wireless link. In the downlink direction of this configuration, the AFPM photodetects the optical signal from a central site and radiates it through the antenna to a mobile terminal, such as a lap-top computer. In the uplink direction, the antenna picks up the radio signal from a mobile terminal and uses it to drive the AFPM. The AFPM in turn modulates and reflects the optical signal back to the central site over fibre.

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Fig. 13. A separate waveguide electroabsorption modulator (EAM) [5] was used to modulate the laser light externally. This modulated light was then optically amplified with an EDFA before being coupled into the 12.6 km SSM fibre. At the other end of the fibre, the optical signal was photodetected by the AFPM, and the resulting electrical signal was further amplified and finally demodulated as in the previous experiment.

Figure 14 shows the measured downlink BER as a function of the 5.189 GHz RF source power and it can be seen that error-free transmission was obtained when the RF power used was −15.8 dBm or higher. The inset within Fig. 14 shows a clear eye diagram of the recovered 68 Mbit/s 2^{23} – 1 PRBS measured using −5 dBm RF power.
with silver epoxy. The p-layer contact pad was epoxied to a metal pin, which in turn was soldered to the radiating side of the antenna through a via-hole in the antenna dielectric material. Figure 16 shows the microstrip patch antenna radiating side.

DC bias was provided to the AFPM through a narrow, high characteristic impedance (90Ω) line. At one end, this line was joint with two radial stubs which provided a low impedance point at 5.2 GHz. Since the line was 3\(\lambda/4\) long at the operating frequency of 5.2 GHz, a very high impedance point was presented at the other end of this line which was connected to a non-radiating edge of the antenna patch.

The amount of radiated power, \(P_{\text{rad}} = R_{\text{rad}} \times i_{\text{rms}}^2\), from the antenna depends on how much AC photocurrent \(i_{\text{rms}}\) is generated and the radiation resistance \(R_{\text{rad}}\) of the location on the antenna where the AFPM is connected. Higher radiated power can be obtained if the AFPM is connected to a point where \(R_{\text{rad}}\) is also higher, provided that the corresponding time constant \(C_{\text{AFPM}} \times R_{\text{rad}}\), where \(C_{\text{AFPM}}\) is the AFPM capacitance, does not reduce the amount of \(i_{\text{rms}}\) going through \(R_{\text{rad}}\). \(C_{\text{AFPM}}\) was measured to be around 260 fF and so if the AFPM was connected to a point where \(R_{\text{rad}} = 100\Omega\), the −3 dB cutoff frequency would be 6.1 GHz which is high enough for operation at 5.2 GHz. Electromagnetic wave simulations using Agilent ADS were performed to locate the point on the antenna patch where \(R_{\text{rad}} = 100\Omega\) and a metal pin was inserted there to connect the AFPM.

A preliminary free-space microwave downlink transmission experiment was carried out with the antenna integrated AFPM functioning as a photodetector and transmitter. A 5.2 GHz optical beat signal was generated by heterodyning two lasers and incident on the AFPM. The AFPM photodetected this signal and radiated it through the integrated antenna. At a distance of 1.4 m, a second identical antenna without an AFPM was then used to receive this radio signal which was further amplified to −31 dBm and detected by a spectrum analyser. Figure 17 shows the experimental arrangement and result.

To our knowledge, this is the first time an AFPM has been directly integrated with a microstrip patch antenna. Further experiments with the AFPM receiving a radio signal and modulating the input light will be carried out in due course.

7. Conclusion

We have designed and fabricated air-bridged AFPMs
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References


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