

Electro-optic modulation using asymmetric Fabry–Perot laser diode amplifiers

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We report the use of laser diode amplifiers, whose facets have unequal mirror reflectivities, as asymmetric Fabry–Perot modulators. Due to the presence of optical gain in these devices we observe modulation of reflected light with both large absolute modulation depth and high contrast ratio.

There is great interest in semiconductor electro-optic modulators for use in optical computing, as spatial light modulators, and for neural network applications. In particular, asymmetric Fabry–Perot modulators (AFPMs)^{1–4} (which are low finesse Fabry–Perot devices in which one mirror is highly reflecting while the other has a lower reflectivity) have received significant attention because they can provide high contrast ratio modulation when operated in reflection. In general (but particularly for high finesse devices), for efficient operation vertical cavity modulators require simultaneous and critical matching of the incident light wavelength, cavity resonance, and material absorption edge. These stringent tolerances place great demands on fabrication and limit effective modulator operation to a narrow wavelength range. Further, although passive (i.e., absorptive) multiple-quantum-well (MQW) reflection modulators can allow high contrast modulation they also exhibit high insertion loss which mitigates against device cascability. Consequently there is a requirement for semiconductor modulators with very low insertion loss or, ideally, gain.

In this letter we describe the use of an asymmetric Fabry–Perot laser diode amplifier (AFP-LDA) as an APM. Since intracavity absorption in the LDA can be easily varied by change of injected current and further since *gain* can be achieved at sufficient bias, we achieve a wider range of reflection and transmission coefficients using the AFP-LDA than is attained with conventional passive devices. We show that AFP-LDAs can function as high contrast optical modulators giving very large modulation depth over a broad range of incident wavelengths.

We have experimentally investigated the modulation properties of AFP-LDAs using the experimental arrangement shown in Fig. 1. Both the laser diode used as modulator and the probe laser diode were channelled substrate planar, large optical cavity (CSP-LOC) structures⁵ with one high-reflectivity (HR) facet and one facet as cleaved. Both devices were temperature controlled to 0.01 °C. The probe laser (“probe”) was maintained at constant bias above its lasing threshold while the AFP-LDA (“device”) was operated over a range of biases below threshold. Single mode probe light at wavelength $\lambda_{in}=870$ nm was passed through a Faraday isolator, variable attenuator, and beamsplitter before being incident on the AFP-LDA cleaved facet. Incident optical power

was typically about a few microwatts. The transmitted and reflected light were monitored simultaneously and the data stored on computer. The phase detuning between λ_{in} and the device FP resonance was varied by changing the device temperature. This detuning was calibrated by altering the device temperature until one device free spectral range was tuned across the fixed probe emission wavelength. The measured change in temperature required to tune between adjacent device FP resonances was 5.9 °C. Therefore, from the measured device longitudinal mode spacing of 4.4 Å, the shift of the FP modes with temperature is 0.75 Å/°C in excellent agreement with the previously measured value of 0.8 Å/°C for the CSP structure.⁵

Measured device reflectivity versus wavelength detuning (relative to the impedance matched resonance position) is presented in Fig. 2 for AFP-LDA bias (I_b) in the range 24 mA $\leq I_b \leq$ 62 mA. For $I_b < 46$ mA, the variation of reflection resonance profile with bias is similar to that observed in a passive APM device. As I_b is further raised, gain occurs at the probe wavelength—the reflectivity becomes greater than 1 and continues to rise. It is also apparent that the reflection profile about resonance abruptly changes from a trough ($I_b < 46$ mA) to a peak ($I_b > 46$ mA). This fact allows *absolute* calibration of the device reflectivity since it may be shown [from Eq. (1) below] that this change in profile occurs when the resonant reflectivity passes through 1. In Fig. 3 we show the variation of device reflectivity at resonance with applied bias (derived from the measurements of Fig. 2, in-

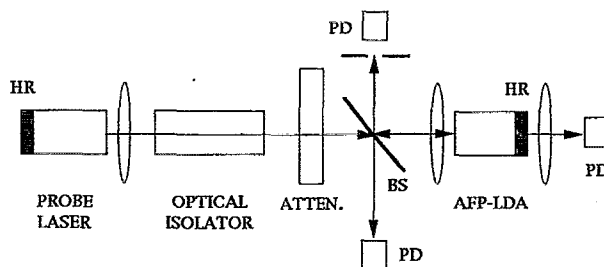


FIG. 1. Schematic diagram of experimental arrangement. As indicated, the probe laser and AFP-LDA device both have one HR facet and the other facet as cleaved. BS: beamsplitter, PD: photodetector, ATTEN: variable attenuator.

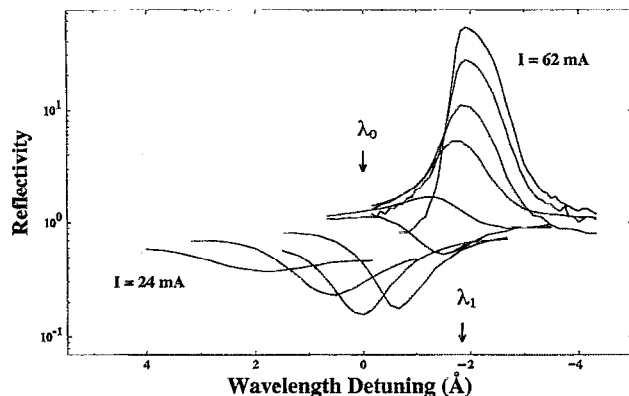


FIG. 2. Measured AFP-LDA reflectivity vs relative wavelength detuning from impedance matching, for $I_b = 24, 30, 34, 38, 44, 48, 53, 56, 59$, and 62 mA. Impedance matching occurs at $I_b = 34$ mA for a wavelength of λ_0 . Maximum device reflectivity is achieved at a resonance position of λ_1 .

cluding some extra results from the same set of data). The measured reflected signal does not fall to its expected value of zero at impedance matching (around $I_b = 34$ mA) due to a background of scattered incident light.

Although the AFP-LDA differs from passive modulators in that gain can be achieved, this additional operating regime (which leads to $R > 1$) is also well explained by standard AFPM theory. Usually, a FP electroabsorption modulator consists of two plane parallel partially reflecting surfaces (of reflectivity R_1 and R_2) separated by distance L , the intracavity medium having an average internal loss α (including material absorption, scattering losses, etc.). When light is incident normal to the cavity the etalon intensity reflection coefficient R can be written⁶

$$R = \frac{(\sqrt{R_1} - \sqrt{R_2}e^{-\alpha L})^2 + 4\sqrt{R_1 R_2}e^{-\alpha L} \sin^2 \Phi}{(1 - \sqrt{R_1 R_2}e^{-\alpha L})^2 + 4\sqrt{R_1 R_2}e^{-\alpha L} \sin^2 \Phi}, \quad (1)$$

where $\Phi = 2\pi N L / \lambda_{in}$ is the single-pass phase change, N is the refractive index of the medium, and λ_{in} is the wavelength of light incident on the etalon. It is clear that R is a periodic

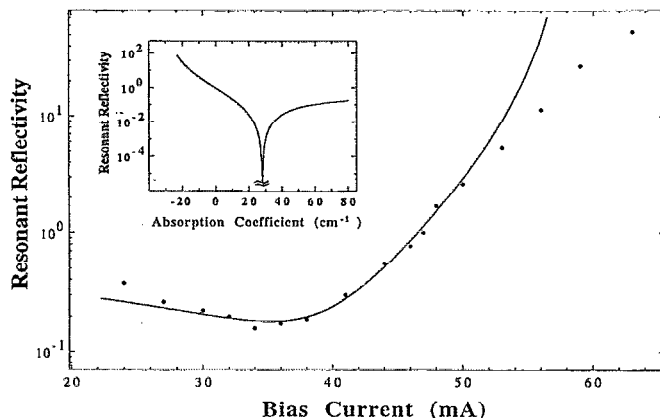


FIG. 3. Measured AFP-LDA reflectivity on resonance vs I_b (points). Also shown is a fit of the calculated curve to the experimental data using an experimentally determined gain-current relation. The inset shows this calculated variation of reflectivity at resonance vs α .

function in Φ , with resonances occurring for $2\Phi = 2n\pi$ (n = integer). In LDAs (in contrast to the shorter passive vertical cavity structures) there are many such FP resonances under the gain curve and consequently AFP-LDAs can operate as AFPMs across this large wavelength range (greater than 20 nm).

For light of fixed Φ incident on a FP cavity, the device reflectivity depends on the mirror reflectivities and on the loss or gain in the cavity. Phenomenologically, gain in a laser diode varies approximately linearly with bias I_b .⁷ The inset of Fig. 3 shows calculated variation of FP reflectivity with α when resonant light is incident at the lower reflectivity mirror. Negative absorption implies gain in the laser diode active region. The device parameters used: $L = 198$ μm , $R_1 = 0.32$, $R_2 = 0.975$, correspond to those of the experimental device. When the front and the *effective* back mirror reflectivities are equal there is total destructive interference at resonance between the beam reflected from the front facet and that returning upon reflection from the back facet (having a double pass through the medium). At this point a minimum occurs in reflection which is apparent in the inset. In general this *impedance matched* condition is reached when $R_1 = R_2 e^{-2\alpha L}$. For this reason AFPM devices can in principle give very high contrast ratio modulation since the value of the minimum in reflection is only limited by scattered light. For AFP-LDAs the impedance matched condition can be achieved controllably by variation of I_b . Additionally, for large bias (i.e., for negative values of α) incident light experiences gain. Consequently, a very large range of reflectivity may be obtained with AFP-LDAs despite gain saturation near to lasing threshold. Figure 3 shows the fit of this calculated variation of resonant reflectivity with the experimental results of Fig. 2. A simple linear relationship derived from experimental measurements^{7,8} is used for the variation of α with I_b , and the experimentally observed background of scattered light of $R = 0.18$ has been added to the calculated curve. The deviation between the experimental and calculated curves at large $|\alpha|$ occurs due to gain saturation at high bias by the incident light (this is evidenced by the slight asymmetry of the device resonance at high bias in Fig. 2)⁹ and the limited range of applicability of a linear gain-current relationship. Overall, reasonable agreement is seen considering the simplicity of the model, perhaps due to the fact that the device is biased above the material transparency point of about 27 mA.

The contrast ratio of modulated light is an important parameter for evaluating modulator performance. From an applications point of view, however, a low insertion loss and a large change in output level are equally important. In Fig. 3, a total range of reflectivity from 0.15 to 53 is available from the AFP-LDA modulator. However, since the carrier density decreases with increasing bias, the carrier density dependent refractive index decreases^{10,11} and shifts the FP resonances to shorter wavelength. Consequently the full range of reflectivity is not available at a fixed incident wavelength for this device. (We note however that due to the small linewidth enhancement factor of quantum-well lasers with strained active regions^{12,13} the shift of resonance position with carrier density should be much reduced so that λ_0

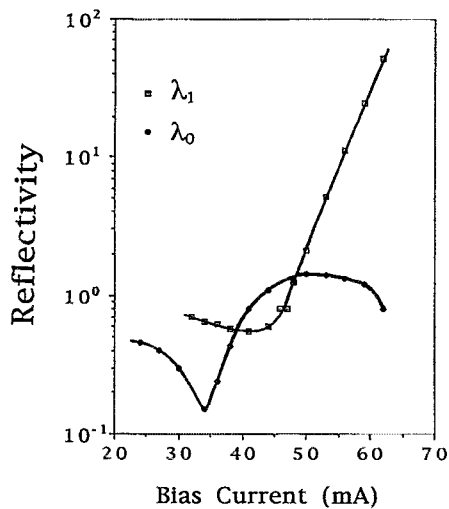


FIG. 4. Measured AFP-LDA reflectivity vs bias for fixed wavelengths λ_0 and λ_1 indicated in Fig. 2. The lines are drawn as a guide for the eye. A contrast ratio in reflection of 10:1 was achieved at λ_0 for a 16 mA change in I_b with reflectivity varied between 0.15 and about 1.4. At λ_1 a contrast ratio of nearly 100:1 was achieved for a 20 mA change in I_b with reflectivity varied from 0.55 to 53 (i.e., 5300%).

and λ_1 would nearly coincide). In Fig. 4 we plot measured device reflectivity vs I_b for the two incident wavelengths indicated in Fig. 2. A contrast ratio of 10:1 was obtained at the wavelength of impedance matching (λ_0), and 100:1 at the resonance position where the maximum reflectivity is achieved (λ_1). It is notable that not only is a good contrast ratio observed but *more importantly the change in absolute reflectivity is very large*. This feature is very attractive for applications where cascability and large fan out are required. We note in passing that the AFPM still provides reasonable transmission performance (at resonance, a transmission range of 0.003 to 1.05 can also be accessed with this device). Therefore, contrast ratios of up to 100:1 in both reflection and transmission can be achieved by changing the bias current by about 15 mA. We note that the poor contrast ratio at λ_0 is due to the large background signal in reflection in our experimental arrangement which limits the decrease in

device reflectivity at impedance matching. Contrast ratios of typically 100:1^{14,15} with insertion losses of around -4 dB have been achieved in passive AFPMs. However, the reflectivity can typically only be varied by about 0.5 and they operate only over a narrow wavelength range. While AFP-LDAs are complicated by the use of a waveguide structure, they do not suffer from the critical design and fabrication constraints of MQW modulators, or from their narrow optical bandwidth.

In conclusion, we have investigated use of active AFP-LDAs as optical modulators and have demonstrated the use of a laser diode as an AFPM. Contrast ratios of up to 100:1 were obtained in both transmission and reflection at a single wavelength. Reflectivity can be varied between 0.15 and 53 and the observed behavior is in good agreement with calculation. The device characteristics compare very favorably with passive AFPM structures, and the active device brings additional benefits of gain, enabling a very large variation of reflectivity in the asymmetric configuration.

- ¹ M. Whitehead and G. Parry, *Electron. Lett.* **25**, 566 (1989).
- ² S. Zumkley, G. Wingen, J. L. Oudar, J. C. Michel, R. Planel, and D. Jager, *IEEE Photon. Technol. Lett.* **5**, 178 (1993).
- ³ M. H. Moloney, J. F. Heffernan, J. Hegarty, R. Grey, and J. Woodhead, *Appl. Phys. Lett.* **63**, 435 (1993).
- ⁴ B. Pezeshki, D. Thomas, and J. S. Harris, Jr., *Appl. Phys. Lett.* **58**, 813 (1991).
- ⁵ J. C. Connolly, T. R. Stewart, D. B. Gilbert, S. E. Slavin, D. B. Carlin, and M. Ettenberg, *Proc. SPIE* **885**, 124 (1988).
- ⁶ M. J. Adams, *Solid-State Electron.* **30**, 43 (1987).
- ⁷ B. W. Hakki and T. L. Paoli, *J. Appl. Phys.* **46**, 1299 (1975).
- ⁸ N. F. Mitchell, Ph. D. thesis, University of Dublin, 1993.
- ⁹ N. F. Mitchell, J. O'Gorman, J. Hegarty, and J. C. Connolly, *Opt. Lett.* **19**, 269 (1994).
- ¹⁰ J. Manning, R. Olshansky, and C. B. Su, *IEEE J. Quantum Electron.* **QE-19**, 1525 (1983).
- ¹¹ N. K. Dutta, N. A. Olsson, and W. T. Tsang, *Appl. Phys. Lett.* **45**, 836 (1984).
- ¹² N. K. Dutta, N. A. Olsson, H. K. Temkin, R. A. Logan, and T. Tanbun-Ek, *IEEE J. Quantum Electron.* **QE-27**, 678 (1991).
- ¹³ T. Ohtoshi and N. Chinone, *IEEE Photon. Technol. Lett.* **1**, 117 (1989).
- ¹⁴ M. Whitehead, A. Rivers, G. Parry, J. S. Roberts, and C. Button, *Electron. Lett.* **25**, 984 (1989).
- ¹⁵ We note however that contrast ratios of more than 1000:1 can be observed by optimization of device design to minimize the off-state reflectivity. This does not enhance modulation depth. D. S. Gerber, R. Droopad, and G. N. Maracas, *IEEE Photon. Technol. Lett.* **5**, 55 (1993).