Air Gap/InP Distributed Bragg Reflectors for Mid-Infrared Applications

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Abstract: We present a systematic study of air gap/InP distributed Bragg reflectors (DBRs) using transfer-matrix method. Reflectivity of various mid-infrared (6 μm) DBR design structures were calculated to obtain the optimum designs for different applications. © 2020 The Author(s)

1. Introduction

The mid-infrared (MIR) region of the electromagnetic spectrum has many absorption lines associated with industrial gas molecules and is thus attractive for sensing [1]. Indium phosphide (InP) with its direct bandgap energy of 1.344 eV is the material choice for MIR regime in the range of 2 – 4 μm [2]. However, for longer wavelengths, inter-sub-band quantum cascade lasers (QCLs), are necessary. These QCLs are commonly based on InP which is lattice-matched to the large conduction band offset $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ heterostructure [3]. However, the lasing efficiency of currently available MIR lasers are still low, hindering its wide applicability. In order to achieve higher lasing efficiency, distributed Bragg reflectors (DBRs), formed from layers of alternating materials with different refractive indices, can be added to the light source to lower the threshold current. Recently, air gap-based DBRs have been experimentally demonstrated an increased facet reflectivity in a QCL there by lowering the threshold current by 11% around 7 μm [1]. In comparison with CVD-grown multilayer DBRs, air gap-based DBRs can be fabricated more easily by common selective etching [1,4].

Here, we systematically study the reflectivity of various air gap/InP DBR designs of λ/4n, 3λ/4n, and 5λ/4n (summarized in Table 1) as a function of incident wavelength (centered around 6 μm), angle, and polarization using the transfer-matrix method derived from Maxwell's equations [5]. The influence of thickness variations on the reflectivity, important when understanding the effect of fabrication tolerance, were also simulated. At 6 μm the refractive index of air and InP were 1.00 and 3.09, respectively and were assumed to be constant in the wavelength range under the studies [6].

2. Design Considerations

DBRs with different designs were simulated for 1 (single) and 3 periods (multi-periods), as illustrated in Figure 1 (a). The simulation results, Figure 1 (b), reveal that single period DBRs give intermediate values of reflectivity around the center wavelength, while 3-period DBRs have very high reflectivities. This result indicates that the single period DBR is more suitable for the front, partial mirror of a laser. Figure 1 (b) also compares different DBR thicknesses λ/4n, 3λ/4n, and 5λ/4n, of these the λ/4n DBR has broader bandwidth but requires the fabrication of thinner pillars and would be more difficult to fabricate. On the contrary, 3λ/4n and 5λ/4n DBRs have narrower bandwidth that may be useful for certain applications and thicker, easier to fabricate layers.

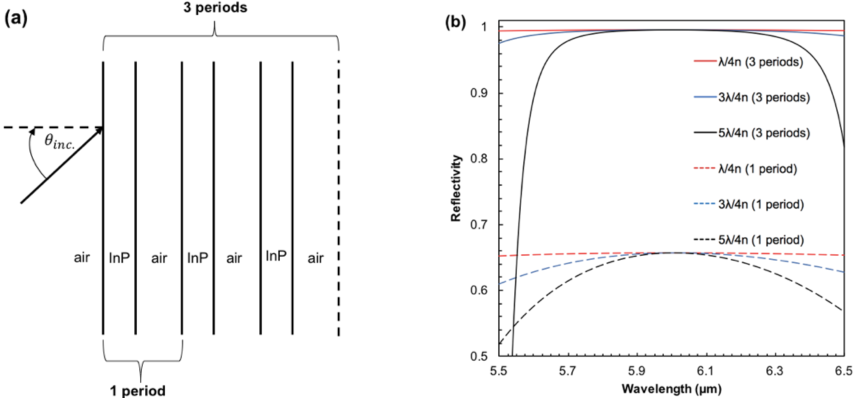

Fig. 1. (a) Schematics of the air gap/InP DBR. (b) Reflectivity vs. wavelength of air gap/InP DBR for various design structures.

Table 1. Layer Thicknesses for Different DBR Designs

DBR design	InP layer (µm)	Air gap (µm)
$\lambda/4n$	0.485	1.5
$3\lambda/4n$	1.46	4.5
$5\lambda/4n$	2.43	7.5

3. Incident Angle and Polarization Dependence

Figure 2 shows the incident light angle (see Figure 1 (a)) dependence of reflectivity for the single period λ/4n design. As the incident angle increases, the reflectivity increases for TE-polarized light but decreases for TM-polarized light. It is important for lab-on-a-chip applications when the DBR is usually coupled to a polarized light source with a certain far-field radiation pattern. Particularly, in QCLs, predominantly TM-polarized light is expected as dictated by the selection rules of the inter-sub-band transitions [7]. For this application, lower reflectivity for larger incident angle could be good to better establish the resonance condition using normal light within the cavity.

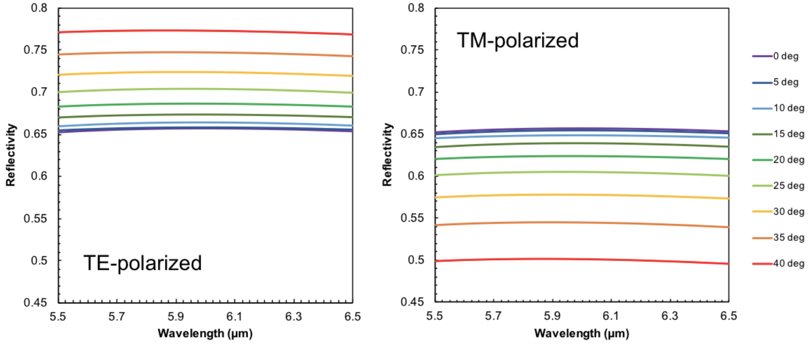

Fig. 2. Incident angle and polarization dependence of reflectivity for the air gap/InP DBR (1 period) with λ/4n design.

4. Thickness Variations

Periodicity also affects the performance stability of a DBR from thickness variations that arise from non-ideal fabrication processes. Single period DBRs are much more stable to the thickness variations than multi-period DBRs, which is true for all design structures. In addition, for structures with the same periodicity, 5λ/4n design is more resilient to the thickness variations compared to λ/4n and 3λ/4n designs. Therefore, in principle, it is highly possible to fabricate single period DBRs with 5λ/4n design using cheap chemical etching without worrying reflectivity degradation.

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