Optical modes at the interface between two dissimilar discrete meta-materials

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Abstract: We have studied theoretically and experimentally the properties of optical surface modes at the hetero-interface between two meta-materials. These meta-materials consisted of two 1D AlGaAs waveguide arrays with different band structures.

OCIS codes: (240.6690) Surface waves; (230.7370) Waveguides.

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1. Introduction

It is a well known fact in many areas of science that the breaking of translational symmetry can lead to new phenomena unique to an interface. For example, surface electronic states in semiconductors owe their existence to the introduction of a boundary [1]. When two dissimilar semiconductor crystals are separated by an interface, new electronic states are formed in the gap between the valence and conduction bands [2]. In acoustics, the boundary is well-known to give rise to surface waves, in this case due to the coupling between transverse and longitudinal modes at the boundary [3]. In electromagnetics, surface waves such as plasmons can exist at the interface between a dielectric and a metal provided that the electron "gas" is excited below its plasma resonance [4]. The coupling between electromagnetic waves and other material resonances are known to lead to a variety of other surface guided modes such as surface exciton polaritons, etc [4].

There has recently been a surge of interest in the optics of artificially structured materials, called meta-materials. Examples of such meta-materials are periodic structures which exhibit many new phenomena due to their unique diffraction properties which arise from the evanescent coupling between adjacent channels [5]. The discrete diffraction behavior of these arrays was first considered by Allan Jones in 1965 and was observed experimentally in 1973 by Yariv's group [6, 7]. It was also demonstrated that under certain conditions the interface between a periodically layered structure and air could support linear TM polarized waves [8]. Periodic arrays have also led to the discovery of additional unique linear optical properties such as anomalous diffraction, multiple allowed bands, Bloch oscillations, the discrete Talbot effect, etc [9-12]. The disruption of translational symmetry by a defect buried in an "infinite" array has been predicted and observed to lead to "defect" modes [13-15]. These modes lie outside the Floquet-Bloch bands associated with the uniformly periodic structures and hence are localized at the defect site. To date, surface localized modes in 1D or 2D arrays have only been observed because of nonlinearity in the form of surface spatial solitons [16-20]. These nonlinear surface waves, sometimes called nonlinear Tamm states (in analogy with Tamm states in solid-state physics [1]) only exist above specific power thresholds, a characteristic predicted in the 1980s for the interface between continuous nonlinear media [21-23].

In this paper we predict and report experimentally the existence of *linear* propagating optical modes located in k-space in a band gap of two periodic meta-materials. It is known

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that the Floquet-Bloch band structure of 1D arrays of channel waveguides can be engineered by varying the channel geometry [10]. We show here that under certain conditions on the interface between two dissimilar neighboring arrays, linear (no threshold power) modes exist with fields localized near the boundary and extending into both arrays. These waves exist by virtue of a strong evanescent coupling between the two arrays.

2. Sample structures and their diffraction patterns

We initially modeled the system numerically in order to establish the range of fabrication parameters needed for observing interface effects [24]. The sample geometry is shown in Fig. 1. First, a finite-difference mode solver was used to evaluate the properties of the isolated channels in both arrays. Based on the overlap of the individual channel fields with their neighbors, there were four different inter-channel coupling strengths, namely c_{ll} (between neighboring channels, left-side array), c_{rr} (between neighboring channels, right-side array), c_{lr} (between interface channel, left-side array to the interface channel, right-side array) and c_{rl} (between interface channel, right-side array to the interface channel, left-side array). The two interface channels are sufficiently different that the coupling coefficients for the gap from left to right, and right to left, are different [25].

The resulting parameters were used to model the continuous-wave (cw) response of the sample. The underlying paraxial equation of diffraction that describes the wave propagation (along z) in this one-dimensional AlGaAs system is:

$$i\frac{\partial U}{\partial z}+\frac{1}{2k}\frac{\partial^2 U}{\partial x^2}+k_0\,V(x)U=0, \tag{1}$$

where U is the envelope of the electric field, x is the transverse coordinate, and $V(x)$ is a function that describes the refractive index distribution of the composite array (see Fig. 1(b)). In addition, $k_0 = 2\pi/\lambda_0$ and $k = k_0 n$, where $n = 3.28$ is the refractive index of $Al_{0.18}Ga_{0.82}As$.

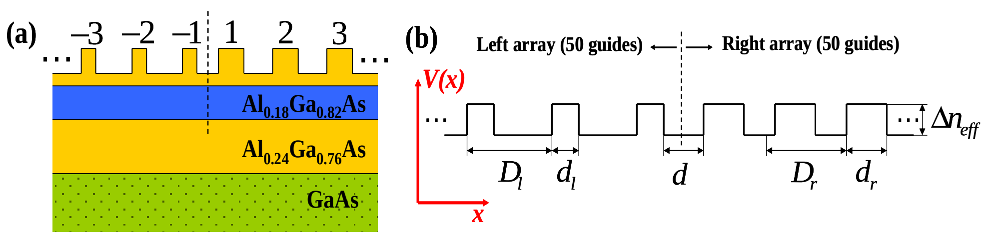

Fig. 1 (a) AlGaAs hetero-interface waveguide array composition. (b) Details of the dimensions of the two arrays where d is the separation between the two dissimilar arrays.

Beam propagation method (BPM) studies of the evolution of the beams inside the sample based on these equations are shown for excitation of a single boundary channel in Figs. 2 and 3 for the following parameters: the period of each array was $D_l = D_r = 10$ µm, the channel widths were $d_l = 2.4$ µm and $d_r = 5.4$ µm, and the separations between the two arrays were $d = 4$, 3, and 2 µm. The corresponding coupling strengths were: $c_{ll} = 530$ m^{-1}, $c_{rr} = 440$ m^{-1}, $c_{lr} = 380$, 540, and 760 m^{-1}, $c_{rl} = 1470$, 1840, and 2300 m^{-1} for $d = 4$, 3, and 2 µm, respectively. Clearly for $d = 4$ µm (Fig. 2) the tunneling across the gap between the two arrays is negligible and the discrete diffraction patterns are those reported previously for the excitation of boundary channels at the individual array edges [16, 17].

#80631 - $15.00 USD Received 6 Mar 2007; revised 28 Mar 2007; accepted 29 Mar 2007; published 3 Apr 2007

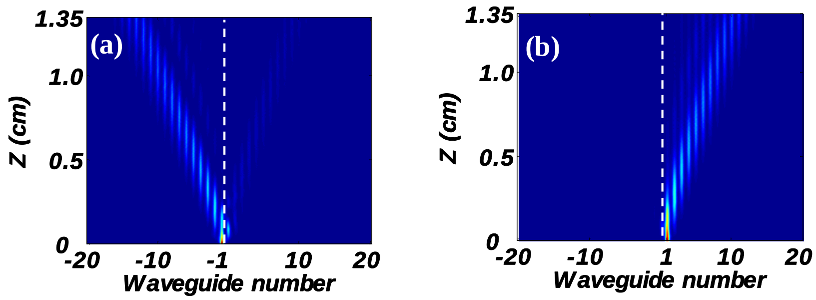

Fig. 2. BPM simulations for d = 4 μm when a single boundary channel of the left (a) and right (b) arrays was excited, respectively. The position of the interface is shown by a dashed line; Z is the propagation distance.

Coupling between the arrays was observed numerically when the inter-array spacing was reduced to d = 3 μm and strong coupling occurred for d = 2 μm. These numerical results are shown in Fig. 3, again for independent excitation of the two boundary channels. Both Figs. 3(a) and 3(b) which correspond to single channel excitation on the left- and right-side of the boundary exhibit diffraction patterns which depart from those associated with the isolated arrays in Fig. 2. In Figs. 3(c) and 3(d), corresponding to d = 2 μm and selective excitation of the left- and right-side channels respectively, there is evidence of strong localization of the electromagnetic field to the two boundary channels.

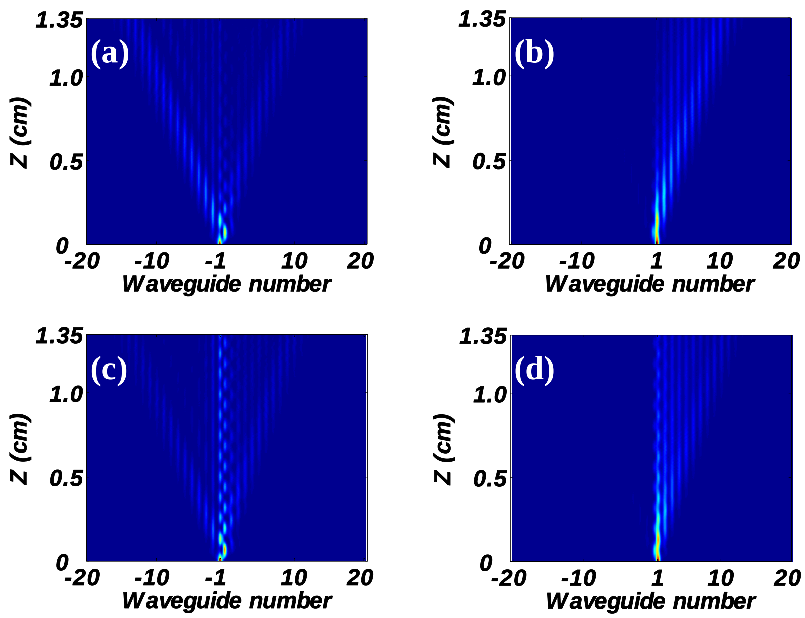

Fig. 3. Simulated discrete diffraction intensity patterns when the distance between arrays is decreased. (a), (b) d = 3 μm; (c), (d) d = 2 μm. Boundary channel of the left-side (a), (c) and right-side (b), (d) arrays was excited.

Based on these simulations, d = 2, 3, and 4 μm were chosen for the sample fabrication. We varied the channel widths, center-to-center spacing, etch depth and spacing between the arrays over a broad range of values. Here D_l and D_r were typically 10 μm, and the d_l and d_r ranged from 2.4 to 5.4 μm. Propagation losses of 0.6 dB/cm, too small for imaging the scattered light from above the sample, were measured for isolated channels, which served as a

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low finesse symmetric Fabry-Perot resonators, using the variation in the transmitted intensity, when the input wavelength was scanned. Radiation at 1550 nm wavelength from a low power cw source (HP8164A/81680A diode laser) was focused onto the first channel's input facet on either side of the boundary. We imaged the intensity distribution at the output facet with an InGaAs line array camera. The experimental results presented in Fig. 4 are in excellent agreement with the numerical simulations. For d = 4 μm, light diffracts away from the boundary for both excitation geometries. These results, both experimental and numerical, imply that linear modes are possible at the interface between the two arrays.

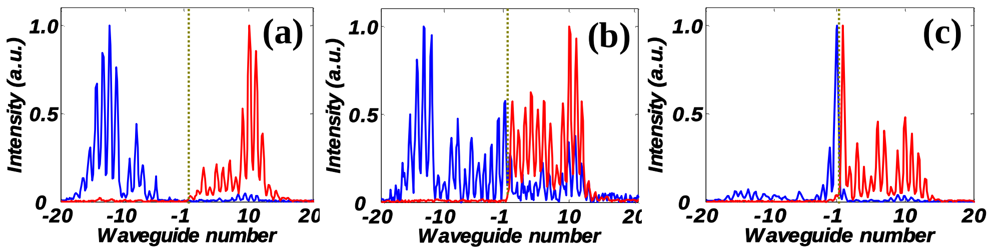

Fig. 4. Intensity patterns observed at the output facet of AlGaAs samples for different separations between two arrays for (a) d = 4 μm, (b) d = 3 μm, and (c) d = 2 μm. Intensity distributions when the first channel of the left (blue curves) and of the right (red curves) array is excited are shown. The position of the interface is shown by a dotted line.

3. Calculation of the band structure of the two semi-infinite arrays

The electromagnetic modes of the composite hetero-structure were numerically calculated for the available samples. More specifically, stationary solutions of Eq. (1) of the form $U(x,z)=\phi(x)\exp[i\lambda z]$, where λ is the propagation eigenvalue of a particular mode (interface or Floquet-Bloch mode), and $\phi(x)$ is the transverse electric field profile, were determined by applying finite differences techniques. For the sample described above (d = 2 μm), the corresponding band structure is depicted in Fig. 5(a). Here the first order bands of the right- and left-side arrays are represented by the red and the blue upper curves, respectively. Also, a part of the second order band of the right-side array is shown in red at the bottom of Fig. 5(a). For this specific sample, only one interface mode was numerically found, with its eigenvalue (red dot in Fig. 5(a)) lying in the gap between the first band of the left-side array and the second band of the right-side array.

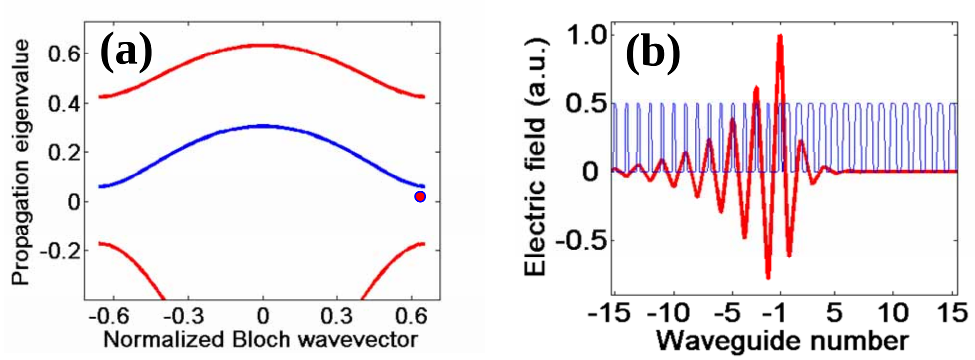

Fig. 5. (a) Band structure of the composite array showing the first order bands of the right-side array (red, top) and of the left-side array (blue, middle), and part of the second order band (red, bottom) of the right-side array. (b) Electric field distribution associated with the interface mode.

#80631 - $15.00 USD Received 6 Mar 2007; revised 28 Mar 2007; accepted 29 Mar 2007; published 3 Apr 2007

The stronger the coupling between the two arrays, the deeper the eigenvalue lies in the gap below the first order band of the left array. The field distribution associated with this mode is "staggered" in each array, i.e. the fields are π out of phase in neighboring channels with an electric field distribution shown in Fig. 5(b).

Of the thirteen different composite arrays available, surface interface states confined to no more than 5-10 channels from the boundaries were predicted for five of them, all of the staggered variety.

4. Experiments on interface modes

We performed a number of experimental tests to verify that the predicted interface modes do exist. The case of strong localization with single channel excitation was already discussed above and clear departure from the classical diffraction patterns was observed. It is clear from the theoretical work that the interface mode fields are π out-of-phase between adjacent channels and are spread over a number of waveguides. Hence a beam tilted to produce a π phase difference between adjacent sites and several channels wide would produce better coupling to the interface modes than the single channel excitation. The experimental results with a Gaussian input beam of FWHM = 35 μm centered at the interface are shown in Fig. 6(c). A BPM code was written based on Eq. (1) and was used to compare directly the output intensity distribution with experiment under the same excitation conditions. The agreement was excellent. Similar excellent agreement was obtained for the other four cases which were predicted to exhibit strongly confined interface modes. When the code was propagated to z = 5 cm, the results agreed completely with the mode solver results.

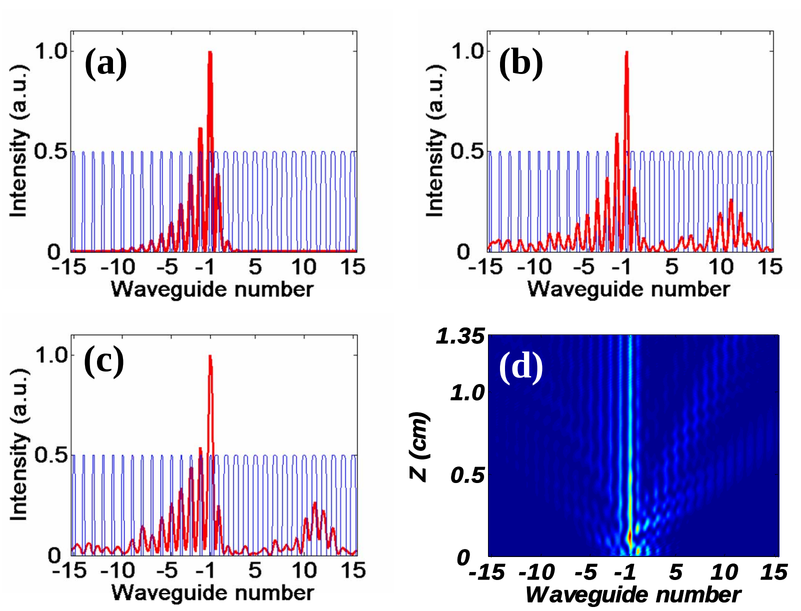

Fig. 6. (a) Intensity distribution associated with the interface mode. (b),(d) Numerically obtained BPM results: (b) output intensity and (d) propagation of the beam as would be seen from the top. (c) Intensity pattern of an interface mode observed experimentally at the output of AlGaAs sample.

In a second set of experiments, the relative phase $\Delta\theta$ between adjacent channels was varied continuously by tilting a wide input beam with respect to the sample facet and recording the beam position at the array output. This technique has been shown to yield the derivative of the dispersion relation for the modes of the array [26]. The results are shown for

#80631 - $15.00 USD   Received 6 Mar 2007; revised 28 Mar 2007; accepted 29 Mar 2007; published 3 Apr 2007

the middle of an array in Fig. 7(a), across an interface with d = 5 μm (predicted to have no interface modes) in Fig. 7(b), and in Fig. 7(c) for an array interface (d = 2 μm) predicted to have an interface mode. The interface modes at the zone boundaries are clearly visible in Fig. 7(c).

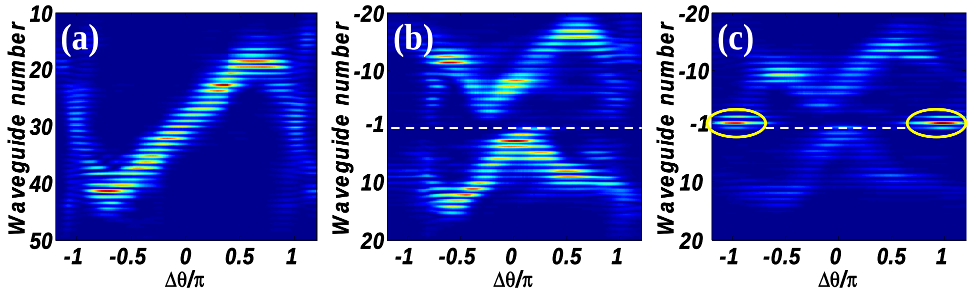

Fig. 7. (a) The derivative of the first band measured in the middle of the right-side array. (b) The structure of the derivatives of the first bands of the left-side array and of the right-side array with an input beam overlapping the interface. This array showed no interface mode, in agreement with theory. (c) Same as (b) but in an array showing an interface mode identified by the yellow ellipses.

A third test was performed by varying continuously the relative phase between adjacent channels and by recording the output intensity distribution. A movie of the interface mode formation based on this procedure is shown below as Fig. 8. Only for phase differences between adjacent channels in the vicinity of ±π is there strong localization of the fields at the interface. Note that for in-phase adjacent channels ($\Delta\theta = 0$), only discrete diffraction is obtained, in agreement with all our theoretical calculations.

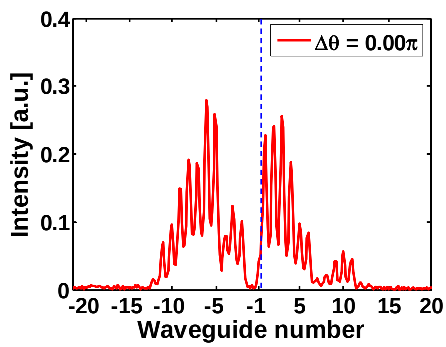

Fig. 8. Movie showing the dependence of the output intensity distribution from a composite array when the relative phase between adjacent channels was varied. Here d = 2 μm.

In different samples it should be possible to have different symmetry interface modes including unstaggered-unstaggered (in-phase, in-phase) fields, and unstaggered-staggered (in-phase, π out-of-phase) fields in the two arrays respectively. We have investigated these possibilities numerically by varying the effective refractive index contrast Δn_{eff} and separation d while keeping other parameters of the two arrays fixed, and have found that all of these modes should exist under different conditions, see Fig. 9.

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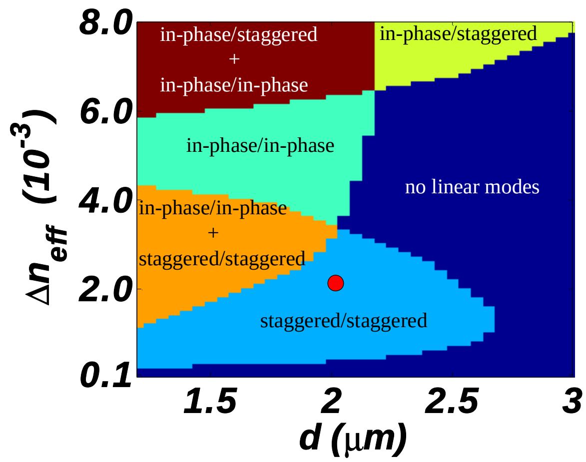

Fig. 9. The regions of existence for interface modes with unstaggered-unstaggered, staggered-staggered and unstaggered-staggered field distributions for coupled arrays such as AlGaAs hetero-structure at 1550 nm. The position of the experimentally investigated interface mode is shown by a red dot.

5. Summary

We have shown that electromagnetic interface states exist at the interface between two meta-materials, in this case two dissimilar arrays of weakly coupled channel waveguides. For the available samples these modes were located at the zone boundaries, just below the first, lowest lying, band and in the gap above the second band of the other array. As a result the field distributions were π out-of-phase between adjacent channels in both arrays.

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