Optical surface waves in periodic layered media[a)]

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A generalized analysis of wave propagation in periodic layered media is applied to the special case of optical surface waves. These waves, confined to the interface between a periodic layered medium and a homogeneous medium, are formally analogous to electronic surface states in crystals. Single-mode surface-wave propagation along the surface of a GaAs-AlGaAs multilayer stack (grown by molecular-beam epitaxy) has been observed experimentally.

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The Kronig-Penney[1] model was introduced to demonstrate the band structure of electronic states in crystals. Tamm[2] considered a semi-infinite Kronig-Penney potential and showed that, under certain conditions, surface states appear. The existence of surface states in a general one-dimensional periodic potential terminated at its potential maximum by a step was also examined by Shockley.[3] He showed that, under appropriate conditions, surface states appeared when the surface "perturbation" was sufficiently small.

The existence of electromagnetic surface waves was suggested by Kossel[4] and later considered in an approximate manner by Arnaud.[5] Recently, the band theory of periodic media[6] was used in an exact analysis of the optical surface waves.

According to the Bloch formulation[6] of electromagnetic wave propagation in a layered medium, the electric field has the form

$$\mathbf{E}(x,z,t)=\mathbf{E}_K(x)\exp(iKx)\exp[i(\beta z-\omega t)], \tag{1}$$

where the coordinate axis is oriented such that the wave is propagating in the x-z plane and the x axis is normal to the layer interfaces. $\mathbf{E}_K(x)$ is a periodic function of x with a period equal to that of the medium.

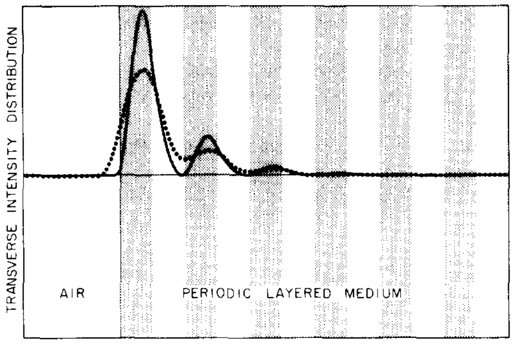

FIG. 1. The calculated transverse intensity distribution for the fundamental surface mode in a periodic layered medium consists of alternating layers of 0.5-μm GaAs and 0.5 μm $Al_{0.2}Ga_{0.8}As$. The dotted line is the convolved intensity distribution using a slit of 0.5 μm.

At a given frequency, there are regions of β for which K is complex,

$$K=m(\pi/\Lambda)\pm iK_i, \tag{2}$$

where m is a non-negative integer.

In an infinite periodic medium, solutions with exponential intensity variation, as in Eq. (1), cannot exist, and we refer to these regions as "forbidden". If the periodic medium is semi-infinite, the exponentially damped solution is a legitimate solution near the surface. The electric field amplitude is described by a decaying exponential in the homogeneous medium and by a standing wave with an exponentially decaying envelope $\exp(-K_i x)$ in the layered medium. A detailed theory of surface waves in layered media can be found in our previous work.[6]

The periodic layered structure in which we observed the surface wave consists of 12 pairs of alternating layers of 0.5-μm-thick GaAs and 0.5-μm-thick $Al_{0.2}Ga_{0.8}As$ on a GaAs substrate. Under these conditions and at the excitation wavelength of 1.15 μm, our theoretical calculation predicts that exactly four surface modes can be supported by the structure. The transverse intensity distribution for the fundamental mode is shown in Fig. 1. The computed Bloch wave numbers of these four modes are given in Table I.

The periodic layered structure was grown by conventional molecular-beam epitaxy (MBE) techniques[7] on a GaAs substrate. Layers were grown at a substrate temperature of 600 °C at a rate of about 1 μm/h. A

TABLE I. Characteristics of surface modes.

Mode	β in units of $(2\pi/\lambda)$	$K\Lambda$	η[a]	α[b] (cm^{-1})
1	3.357	$\pi+i(7.233\times10^{-1})$	2.89×10^{-8}	2.6×10^{-5}
2	3.185	$2\pi+i(5.568\times10^{-2})$	2.63×10^{-1}	6.3×10^{1}
3	2.927	$3\pi+i(2.183\times10^{-2})$	5.92×10^{-1}	1.7×10^{2}
4	2.490	$4\pi+i(8.109\times10^{-3})$	8.23×10^{-1}	3.2×10^{2}

[a] η is the (intensity at substrate)(intensity at surface)$^{-1}$.
[b] α is the attenuation coefficient.

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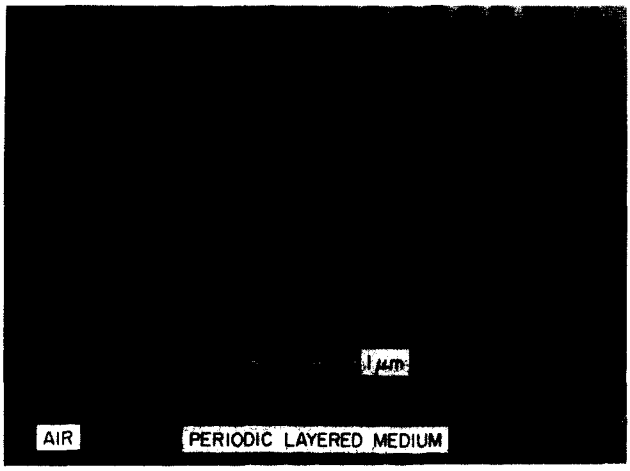

FIG. 2. A phase-contrast photograph of a cleaved section of a layered medium composed of alternating layers of GaAs and $Al_{0.2}Ga_{0.8}As$. The dark layers are 0.5 μm GaAs and the white layers are 0.5 μm $Al_{0.2}Ga_{0.8}As$.

phase-contrast photograph of the structure's cross section is shown in Fig. 2.

Our experimental setup for measuring the mode intensity profiles has a resolution limit of ~0.5 μm consequently, in order to resolve the field distribution of the surface waves, we need to choose a sample with a period Λ at least 1 μm. For samples with large period Λ, the number of surface modes increases linearly as a function of Λ. This introduces the difficulty of resolving admixtures of surface modes. As a compromise, we chose a sample with a period Λ of 1 μm. This structure still supports four surface modes (see Table I). Fortunately, these higher-order surface modes are extremely lossy in a sample with a finite number of periods. Even if we assume that the modes are excited equally, the lossy modes will decay to relative insignificance provided the sample is long enough. We chose a sample 15 mm long, and indeed observed the fundamental mode ($m = 1$) only.

The intensity distribution of the surface waves was obtained by focusing the output of a 1.15-μm He-Ne laser on the cleaved edge of the sample and by scanning the magnified (100×) image of the output edge[8,9] past a narrow slit (~50 μm) and detector combination. The resulting intensity distribution is shown in Fig. 3. This measured distribution is in excellent agreement with the theoretical prediction, Fig. 1, if we convolve the latter with an instrumental window function ~0.5 μm wide. The result of this convolution is shown in Fig. 1.

Because the number of periods in the structure is finite, the intensity at the substrate is not exactly zero (i.e., the surface modes are "leaky"). The calculated attenuation coefficient of each surface mode due to the resulting losses into the substrate, but neglecting the loss due to bulk absorption and surface scattering, is given in Table I. The attenuation coefficient decreases exponentially as the number of periods increases. A rough experimental determination of the mode loss based on comparing the outputs of a number of samples with varying lengths under similar input conditions yielded $\alpha < 10^{-2}$ cm^{-1} for the fundamental mode. The higher-order modes are too lossy to be seen even in a sample 1 mm long. It is possible that continuum modes may be excited at the input surface. However, these continuum modes are all leaky. For a sample 15 mm long, the intensities of these modes are extremely small at the output surface. Interference fringes due to surface reflections can hardly be seen in a sample 10 mm or longer. They are usually seen in a sample 5 mm or less whenever the sample is moved transversely across the focused laser beam.

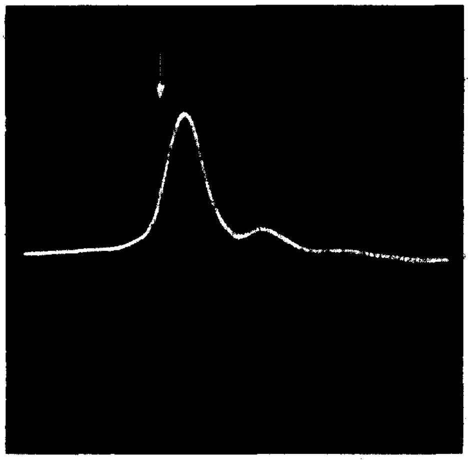

FIG. 3. Measured transverse intensity distribution of surface waves in a layered medium 15 mm long. The horizontal scale is about 0.5 μm per (big) division. The surface of the structure is indicated by the arrow.

In conclusion, the optical surface waves in a GaAs-$Al_{0.2}Ga_{0.8}As$ periodic layered medium have been observed. The experimental results are consistent with the theoretical calculations. This observation also demonstrates the optical analog of electronic surface states in crystals.

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