II. MICROWAVE SPECTROSCOPY*

Academic and Research Staff

Prof. M. W. P. Strandberg
Prof. R. L. Kyhl
J. D. Kierstead

Graduate Students

J. U. Free, Jr.
J. K. Raines
A. Tachagumpuch

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Second-Harmonic Spectroscopy

This research is directed to the discovery and demonstration of useful nonlinearities in quantum-mechanical systems. The work includes both theoretical and experimental investigation in the microwave region.

It is fairly evident that one should be able to observe nonlinear effects in the interaction of lasers with matter. A 1-MW laser can create an electric field a few volts per angstrom in matter. Since this is on the order of atomic fields, it is not surprising that nonlinear interactions are observable in matter not possessing a center-of-inversion symmetry. In contrast, it is certainly not evident that nonlinear effects can be observed from the interaction between matter and microwave sources of a few watts. Resonance between the field frequency and the energy levels of the matter, however, enhances the nonlinear effects by many orders of magnitude. Furthermore, if a static magnetic or electric field is applied, centro-symmetric matter such as a gas can give rise to observable nonlinear interaction. Since microwave wavelengths are of the order of the sample size, the problem of phase matching, which can be a limitation in the observable laser nonlinear effect, is easily dealt with.

That the nonlinear effect is not trivial compared with the linear effect may be seen from the following argument: In normal, linear spectroscopy at microwave frequencies, sample saturation ultimately limits the observable signal size. A small sample in a cavity will be saturated with a power on the order of a microwatt. Since we can operate at a frequency of one-half the matter resonance frequency when studying resonant nonlinear interactions, saturation can be avoided and a power level of watts may be used to produce a signal. Under the proper conditions this signal can equal or surpass the maximum available absorption signal. Finally, since the signal is observed at a frequency twice that of the source field, the source noise does not introduce an additional limitation to the sensitivity of the observation.

A preliminary experiment has been done to evaluate empirically the sensitivity of a second-harmonic EPR spectrometer.[1]

M. W. P. Strandberg

References

1. M. W. P. Strandberg, Quarterly Progress Report No. 107, Research Laboratory of Electronics, M.I.T., October 15, 1972, p. 3.

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2. Dielectric Waveguide Calculations

Dielectric waveguides and resonators without metal walls can be used to advantage in microwave networks, The use of materials with very high dielectric constant (rutile, titanates, and tantalates, for example) reduces the size needed for elements in integrated circuits. The addition of metal walls would in many cases increase losses and complicate manufacture.

We are continuing to develop programs for calculating field patterns of rectilinear dielectric waveguides with $\epsilon \gg \epsilon_o$. The case we are studying first is that of large aspect ratio $b \gg a$ (thin slab in cross section). The first computer results for the lowest modes are now being checked. These results can be compared directly with those for the vanishingly thin dielectric ribbon which we have obtained previously. The work will be extended to guides with more nearly square cross section and then to rectangular resonators.

R. L. Kyhl

A. WORK COMPLETED

1. LOW-TEMPERATURE BEHAVIOR OF RADIO-FREQUENCY SURFACE IMPEDANCE IN METALS

Joint Services Electronics Programs (Contract DAAB07-71-C-0300)

M. W. P. Strandberg

This research has been completed by R. M. Langdon, Jr., and submitted to the Department of Physics on August 1, 1972 in partial fulfillment of the requirements for the degree of Doctor of Philosophy. A summary of the thesis follows.

The surface impedance of a boundary between two media is defined and is shown to provide a measure of the energy absorbed or stored in a medium. The behavior of the surface impedance of a metal in the absence of a magnetic field as a function of frequency and electron mean-free path is reviewed; "classical" and "anomalous" skin-effect conditions are contrasted. The addition of a magnetic field bends the conduction electrons into orbits about the field direction, changing the "nonlocal conductivity" (current response to a delta-function electric field) and affecting the surface impedance in a manner that depends on electron reflection at the surface. Some previous measurements and calculations of magneto-surface impedance are briefly reviewed.

The experimental apparatus was based around a Pound-Knight-Watkins oscillator with the sample included in its tank circuit. If the surface impedance of the sample is changed by a magnetic field, the resulting changes in the oscillator RF amplitude are proportional to the real part of the impedance change. The samples were monocrystalline wafers of gallium in a dewar of liquid He whose temperature was adjustable, by means of a vacuum pump, from ~2° to above 12°K. A modulated dc magnetic field was applied to the sample. Changes in the oscillator RF amplitude were either displayed directly in real time as a synchronized oscilloscope trace, or, for small modulation excursions, were phase-detected and their amplitude recorded as a measure of Re [dZ/dH].

Two semianalytical mathematical methods are developed for calculating approximately the magneto-surface impedance of a semi-infinite metal. We assume, in the first case, completely diffuse surface reflection, and in the second, reflection that is specular for co-angles of incidence less than a critical θ_c and diffuse for greater co-angles. For use in the first case a way is found to expand the nonlocal conductivity in the unbounded metal, and its Fourier transform, in powers of H^2. The result, from a formula which assumes the conductivity to be independent of distance from the surface, is a magneto-surface resistance behaving as $Z_o(1+\ell^{4/3}H^2)$ for large ℓ. In the second case the conductivity is approximated by a pure logarithm of the difference of the arguments with an amplitude depending on the distance of one argument from the surface. This form is used in a variational expression that was solved numerically by computer. The results are qualitatively similar to those of a more exact, but completely numerical, published calculation, but depart quantitatively from them in the limit of the long mean-free path.

We used the model for specular reflection to interpret the experimental results. The position of the minimum in R(H) observed at ω_{RF} = 5 MHz, H = several tens of oersteds, and T ~ 2-5°K gives a value of $\theta_c \sim 8°$ for gallium crystals grown in a mold of Lucite coated with carbon black and ~1° for crystals grown in an uncoated mold. The behavior of the curvature of the Re [Z(H)] signal vs temperature, however, is not in agreement with the combined results of the approximate mathematical methods. Further exact numerical calculations must be made to resolve the question of whether this discrepancy arises out of errors inherent in the approximations or out of differences of gallium from the physical model assumed. The frequency dependence of the minimum positions H_{mm} observed in measurements from 850 kHz to 17 MHz tentatively confirms the prediction of the completely numerical calculation that $H_{mm} \propto \omega^{1/3}$.

B. WORK IN PROGRESS

1. PROPAGATING WAVES ON A HIGH DIELECTRIC SLAB

Joint Services Electronics Programs (Contract DAAB07-71-C-0300)

J. K. Raines

Field solutions have been obtained for propagating waves in a slab of high dielectric ($\epsilon/\epsilon_o \to \infty$) material, surrounded by free space. These are solutions of a more general equation that describes propagating waves in a high dielectric waveguide of any cross section.

$$k_z^2\vec{E}_T - \nabla_T(\nabla_T \cdot \vec{E}_T) = \frac{\omega^2\mu_o\epsilon}{2\pi}\int_A d^2r' \left[k_z^2\vec{E}'_T - \nabla'_T(\nabla'_T \cdot \vec{E}'_T)\right] K_o(k_zR)$$

$$+ \frac{\omega^2\mu_o\epsilon}{2\pi}\int_A d^2r' \, \nabla'_T[K_o(k_zR)\nabla'_T \cdot \vec{E}'_T], \tag{1}$$

where

$\vec{E}_T = \vec{E}_T(\vec{r}_T)$

$\vec{E}'_T = \vec{E}_T(\vec{r}'_T)$

$R = |\vec{r}_T - \vec{r}'_T|$

K_o = modified Bessel function.

The boundary condition

$$\hat{n} \cdot \vec{E}_T = 0 \tag{2}$$

is also required for bound waves.

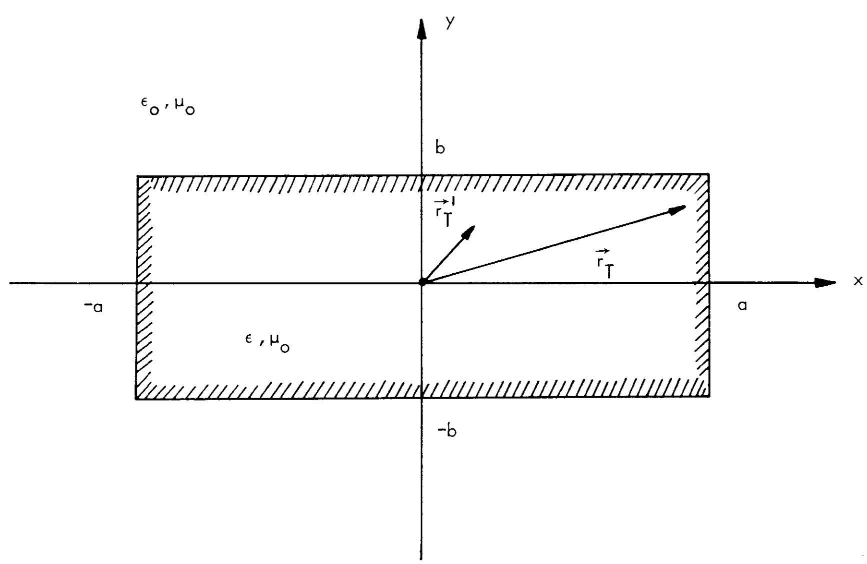

Fig. II-1. Coordinate system for slab waveguide. Aspect ratio = a/b.

Equations 1 and 2 determine the transverse electric field, and the remaining fields follow uniquely from Maxwell's equations

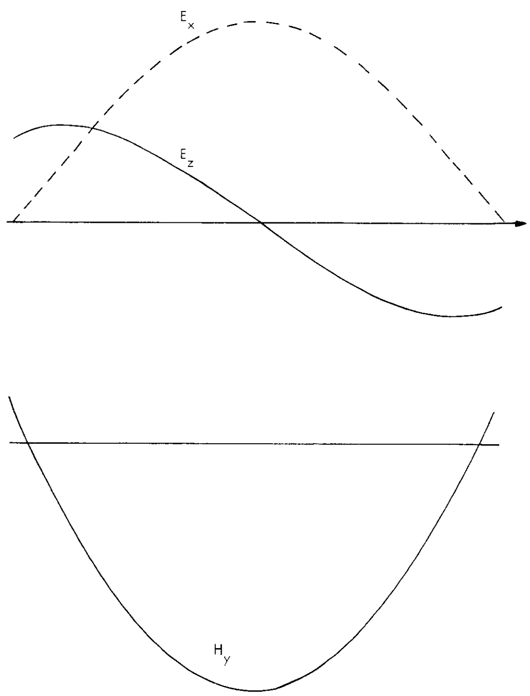

Fig. II-2. Lowest mode symmetric in E_x.

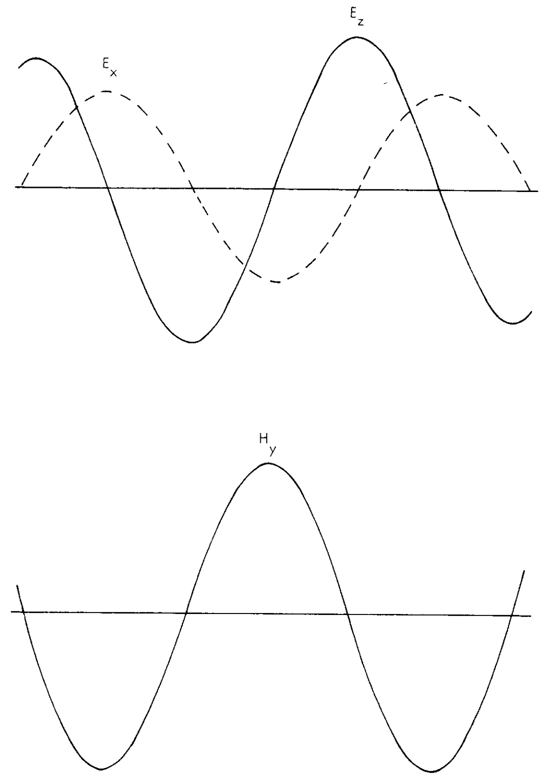

Fig. II-3. Second mode symmetric in E_x.

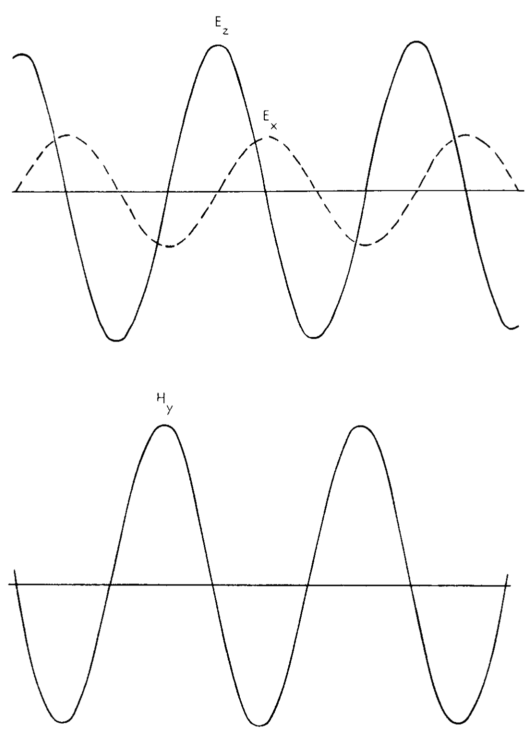

Fig. II-4. Third mode symmetric in E_x.

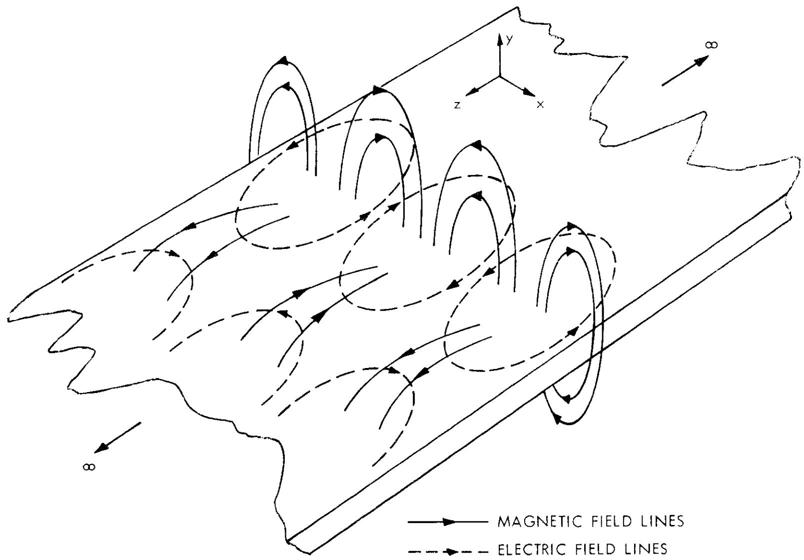

Fig. II-5. Second symmetric mode of thin guide.

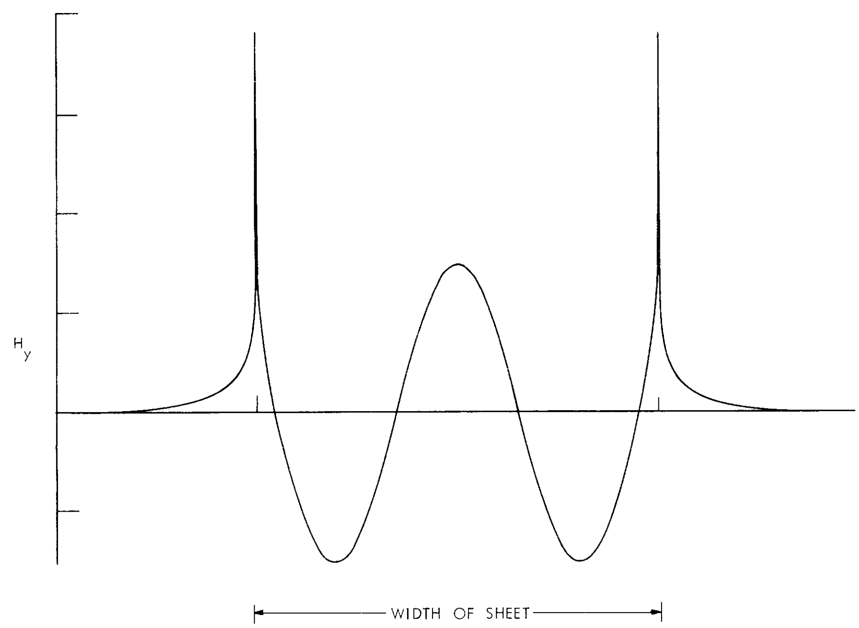

Fig. II-6. Second symmetric mode of ribbon.

$$\nabla \cdot \epsilon \vec{E} = 0$$

$$\vec{H} = \frac{j}{\omega \mu} \nabla \times \vec{E}.$$

For a rectangular cross section, the second term on the right side of Eq. 1 describes singularities in the magnetic fringing fields. As the cross section degenerates to a ribbon, the singularities become logarithmically unbounded.[1] For the slab, the singularities are less severe, and decrease as the wave number k_z increases (Fig. II-1).

For a slab with aspect ratio 10, Eq. 1 has been solved by using the method of moments.[2] The trial functions are Legendre polynomials multiplied by $(1-x^2)$ or $(1-y^2)$ so that Eq. 2 is satisfied identically. These functions proved a fortunate choice. The fields for the first mode are adequately represented by only three terms, and for the third mode (symmetric in E_x) only six terms are required.

Equation 1 describes an eigenvalue problem. That is, for a given propagation number, solutions exist only for discrete ω. Thus in solving for the fields, a dispersion curve is also obtained. Work continues to obtain solutions for any aspect ratio.

Some sample results for 3 modes are shown in Figs. II-2 through II-4. In all cases the aspect ratio is 10:1, and $k_z\sqrt{ab} = 1$. Figure II-5 is a 3-dimensional sketch of Fig. II-3. Figure II-6 shows H_y for the ribbon mode ($k_z = 0$) corresponding to the second mode in Fig. II-3.

References

1. R. L. Kyhl, "Electromagnetic Waves on High Dielectric Constant Ribbon," Quarterly Progress Report No. 99, Research Laboratory of Electronics, M. I. T., October 15, 1970, pp. 3-5.
2. R. F. Harrington, Field Computation by Method of Moments (The Macmillan Co., New York, 1968).