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INTRODUCTION

The objective of the work reported here is to develop a miniature broad-band electric field probe capable of measuring the total electric field with a flat frequency response from 915 MHz to above 10 GHz in free space. In addition, this small probe is to be used for measuring fields within animal tissue or tissue equivalent materials at frequencies below 3 GHz, where the foreshortened wavelength makes microminiaturization imperative.

The problems of near electric field measurements have been discussed in the literature.[1,3] It has been pointed out that for proper measurement of uncharacterized electric fields (unknown direction, frequency, and modulation) under near-field condition, an isotropic probe with low scattering characteristics or small field interactions is desired. In 1969, Rudge and Knox[1] showed that an electrically short dipole antenna (wing length of $1/4\lambda$ or less) with discrete diode detectors provides a probe of high impedance that minimizes dipole currents, thus minimizing field interaction and back scatter. In 1970, the work of Bowman and colleagues[2] demonstrated the feasibility of using three such dipoles in an orthogonal array to provide isotropic reception. This design employs three diode detectors with high resistance leads that are effectively transparent to the field. The high-resistance leads, which convey the detected signal to appropriate readout electronics, cause minimum scatter of the field and thus do not disturb the isotropicity of the receiver.

Isotropic Reception Requirement

The necessity for isotropic reception in an electric field probe arises when the orientation of the electric field vector at the point of measurement is unknown. This is particularly true of near-field hazard assessment of leakage or radiation from microwave devices. Natural simplifications do occur in certain cases. For example, microwave ovens render total isotropic reception unnecessary. In this case, one can predict that energy will radiate outward from the large metal surface of the oven front and that the electric field vector will be in a plane parallel to this surface. The latter follows from a theoretic examination of radiation from a slot source. Other situations are not so easily predicted or simplified, as in near-field radiation from a diathermy "type c" applicator or marine radar unit, in which strong radial components of the electric field may be present. For implanted measurements, similar uncertainties of field orientation may exist due to the effects of focusing or multiple scattering. This situation could be compounded by nonuniform exposure fields. Three orthogonal dipoles, however, provide the required isotropic reception, if the sum of the squares of all electric field components is taken.

Minimal Field Interaction Requirement

The necessity for minimal perturbation or low-level scattering of fields results from the close proximity of source and receiver or from the presence of dielectric boundaries. A low-impedance receiving device that contains large current flow will reradiate, or generate, back scatter. The scatter or reradiation will interact with the source or be reflected from nearby boundaries, which produces a significant alteration of the field at the measurement point. Such effects can be minimized by using a high-impedance device, such as a short dipole. In most cases of hazard assessment, the fields measured are large enough, so that signal sensitivity is not a problem. For low-level laboratory evaluation of fields within dielectric media, trade offs of antenna wing length versus field levels may be required. Also, scatter within dielectric materials may not be as significant for electric field measurements due to the attenuation of the scattered wave in the medium, if field assessment is the only objective. This will, of course, affect the energy and temperature distributions within the medium but does not necessarily render an electric field measurement at a point entirely meaningless. Such measurements within dielectric media must be taken with extreme care and, in all cases, significantly far away from all boundaries.

An additional benefit of the short dipole is its broad-band nature. At frequencies for which the wing lengths are less than $\lambda/10$, the dipole is capacitive. Termination of the dipole by a leadless diode introduces no resonances below frequencies for which the total dipole length is $\lambda/2$ (because the diode is basically capacitive). A dipole 3 mm long, terminated in a leadless diode, should have a theoretic resonance at 50 GHz and a relatively flat frequency response below 10 GHz. The radiation resistance of the short antenna is frequency dependent, but this resistance is very small compared to the total dipole impedance, which yields a minimal variation in detected signal with frequency.

Dipole Array

It is with the above considerations that we began the development of a 3-mm orthogonal dipole array that could be ultimately employed as an implantable probe. The first design proposed attempted to have the centers of the three dipoles coincident. This was accomplished with a single chip that contains nine diodes, three of which were used as detectors. All diodes had a common anode. In effect, this tied the grounded side of the three dipoles together. The net effect was that all three diodes received a partial signal from each dipole, which destroyed the ideal isotropic receiving pattern of the probe. All other approaches with a 3-mm common center configuration were impractical due to physical restrictions. This led to a theoretic reconsideration of the orthogonality requirement in relation to the position of dipole centers.

It is readily observed from the field equations of a short electric dipole found in most texts on antennas that two orthogonal dipoles will not interact if a line that connects their centers is perpendicular to at least one of the dipoles. This condition is the same as stating that one dipole antenna is confined to a plane perpendicular to the second dipole. This plane must pass through the center of the second dipole. The first dipole will detect no radiated fields from the second, because the radial component of the electric field of the second is zero in that plane and the θ component is perpendicular to that plane. The second dipole will detect no radiated fields of the first dipole due to symmetry. (That is, no net voltage will be induced across the dipole, because the fields seen by one wing of the dipole will be equal and opposite to fields seen by the other wing of the dipole.)

With the addition of a third orthogonal dipole, the condition of noninteraction of radiated fields must be preserved. Thus, between any two of the three dipoles, a line drawn through the center of both must be perpendicular to at least one. Consideration of this geometric constraint leads to the conclusion that the only acceptible solution is that a straight line must connect the centers of all three orthogonal dipoles and this line will be orthogonal to two dipoles and collinear with the third.

I-Beam Configuration

The configuration chosen meets the above criteria (FIGURES 1a & 1b). Note that three substrates are joined in a "I"-beam configuration. Each substrate contains a dipole, beam lead diode, and a pair of high-resistance leads. All three dipoles are orthogonal. A line that extends along the length of the center dipole passes through the center of all three.

Diode Detector

The choice of the appropriate type of detector diode and its package is critical to the performance of any microwave detector. The Schottky diode offers the broadest square-law dynamic range and frequency coverage available in microminiature monolithic form. The beam lead configuration of the diode chip (FIGURES 2a & 2b) is ideal for a planar dipole detector, because it possesses minimal parasitic package reactances (0.05 pF, 0.1 nH), low device capacitance (0.15 pF), and mounts across the dipole center gap without any additional bonding wires. These bonding wires, which are used with nonbeam lead devices, tend to act as extraneous antenna elements, introducing a degradation of the pattern and polarization characteristics of

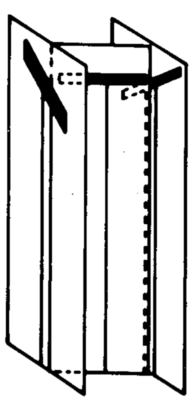

FIGURE 1a. Orthogonal detector array.

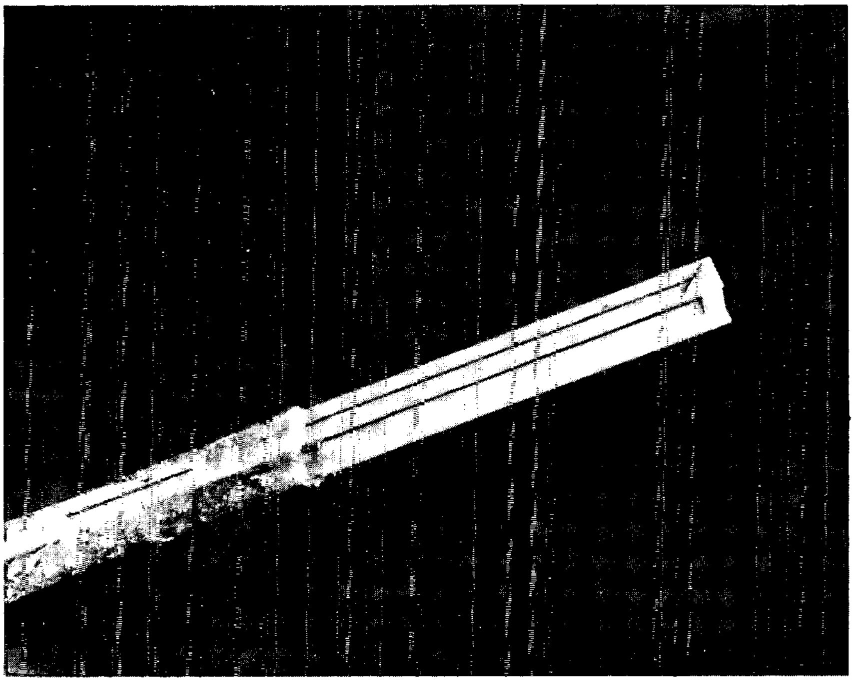

FIGURE 1b. Orthogonal detector array (I beam).

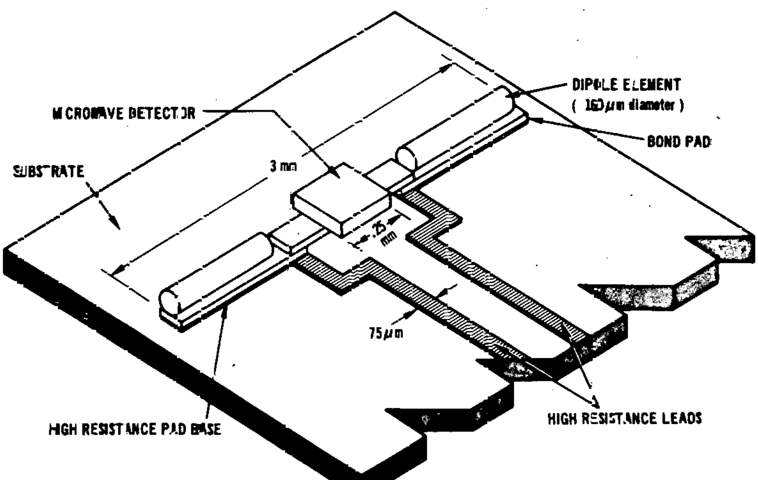

FIGURE 2a. Single-dipole detector configuration.

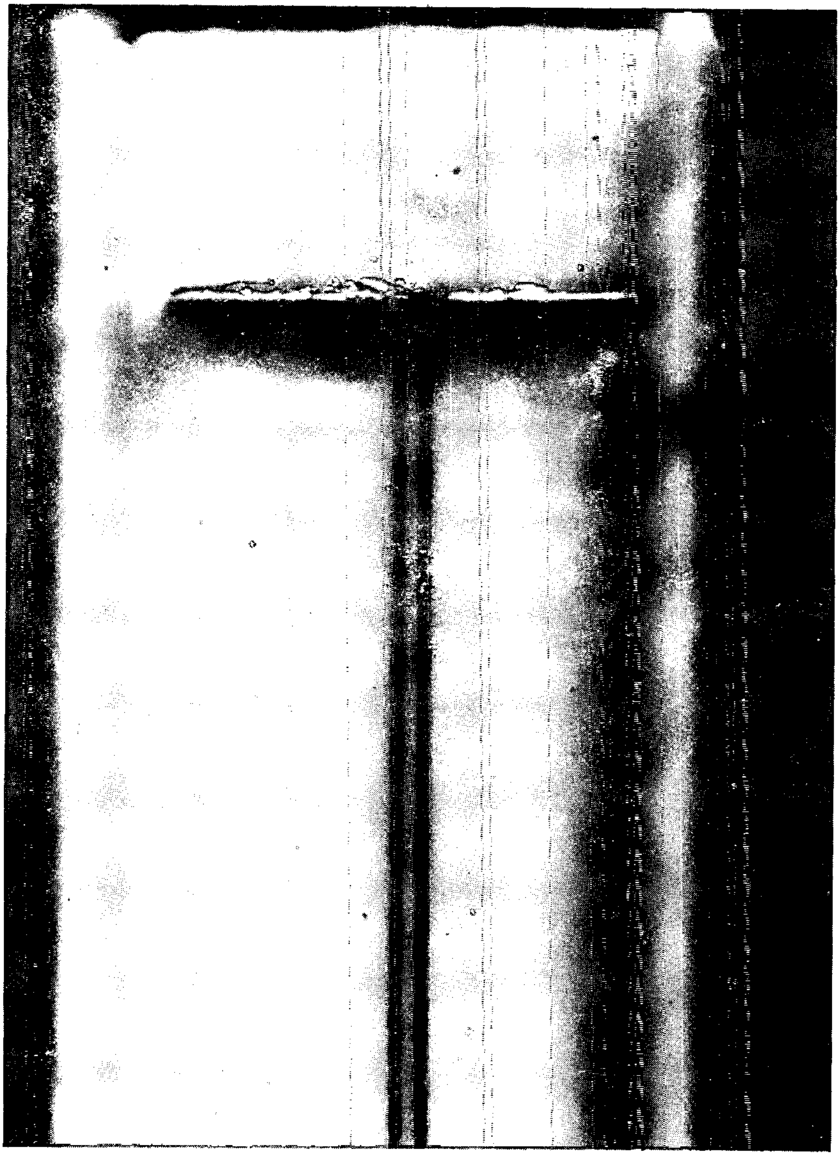

FIGURE 2b. Single-dipole detector substrate.

the detector. An X-band diode chip was used in the existing electric field probe. The chip size of 0.25 mm and its lead configuration were ideal for mounting across the dipole center gap. The only undesirable feature of this device is its requirement of forward bias (10–100 μA) for optimum low-level detector performance. Forward biasing of the diode is not incorporated in the electric field probe because of the complexity it would introduce in the dc preamplifier circuitry used with the probe. Therefore, degraded sensitivity is to be expected at low electric field levels. Discussions of this problem with device manufacturers led to the discovery of a new experimental device, the zero-bias Schottky diode, that alleviates the low-level detector problem and has a significantly better detection efficiency (6–10 dB).

A beam lead zero-bias device will soon be evaluated in the existing probe. This device is dimensionally similar to the presently used diode.

High-Impedance Leads

The design of high-impedance leads becomes more critical as the size of the dipole elements is reduced, because these leads can act as parasitic antenna elements or as scatterers, which degrade the pattern and polarization characteristics of the individual dipole detectors.

An experiment was performed to evaluate the effects of these leads as parasitic antenna elements. A set of high-impedance leads and a diode were fabricated on an alumina substrate. No dipole elements were present on this test fixture. The test substrate was placed in a plane wave exposure situation (F = 2450 MHz). An aluminum shielding tube, covered with microwave absorber, was placed over the base of the substrate. The detected signal vs unshielded lead length, referenced from the tip, was recorded. This provided an indication of the magnitude of the lead pickup and indicated the portions of the structure that were acting as parasitic antenna elements. It was found that only the leads in the immediate vicinity of the diode chip (1 cm) produced pickup. This occurred because the signal picked up by the remaining lengths of the leads was attenuated as it propagated toward the diode. A second check was made by shielding only the area around the diode with a 2-cm band of foil placed around a glass test tube that covered the probe. No detected signal existed under these conditions.

Another experiment was conducted to evaluate the effects of lead spacing on signal pickup. The first set of leads tested consisted of resistive strips (6 kΩ/cm), 6 cm long and 0.25 mm wide, spaced 0.25 mm apart. A second set was identical, except that the spacing between leads was greater (0.75 mm). Signal picked up from the widely spaced leads was of the order of 10 dB greater than the pickup from the first set for an exposure to a 250-V/m (17 mW/cm^2) plane wave. The reduced pickup from closely spaced leads indicated that the increased capacitance was acting to suppress the unwanted signal from the leads. To assure increased effectiveness, the final lead configuration was designed with higher resistance and inductance per unit length by making the lines narrower, 0.075 mm. The capacitance between leads was also increased by spacing the leads 0.075 mm apart. This configuration was used with a 3-mm long dipole, and it yielded a detected signal, virtually all of which was derived from the dipole rather than from the leads, as determined by polarization tests that will be described later in this paper. It is clear that the influence of the leads is critical for small dipole detectors, because improperly designed leads may induce signals that overwhelm those that are derived from the dipole.

Probe Fabrication

Several materials, assembly techniques, and configurations were tried during development before arriving at the present microwave probe. The scheme described here proved most successful with respect to ease of fabrication and performance.

Only the salient aspects of fabrications are presented for brevity. Undefined descriptive terms are identified in FIGURE 2.

Alumina wafers, 5.0 cm × 7.5 cm × 0.25 mm, were sputter coated with high-purity chromium to a sheet resistivity of 120 Ω/square. The chrome was etched, with standard photolithographic techniques, to form high-resistance leads. Each lead, 6.25 cm × 76 μm, has a resistance of approximately 100 kΩ; each pair that belongs to a single dipole substrate is matched to within 2%. An alumina wafer provided 20 probe substrates (7.0 cm × 0.30 cm × 0.25 mm).

Next, a bondable surface was required for mounting leads, dipole elements, and microwave diodes. Chrome-gold was used to define these regions. The bond pads were delineated by deposition through an electroformed gold mask 20 μm thick supported by 80-μm thick Kovar®. Chrome was vacuum deposited to a thickness of 3 nm, followed by 1- or 5-μm thick gold. The thinner gold was used for single-component gold epoxy attachment, and the thicker gold was employed for tin-silver reflow solder attachment; the latter method was preferred.

Each wafer was waxed down and cut into individual probe substrates with a diamond saw. A completed substrate consisted of a pair of high-resistance leads, two mounted dipole elements (160-μm diam. × 0.125-cm rods), a beam lead microwave detector diode (0.25 mm × 0.25 mm) with beam leads extending 0.2 mm from opposite sides, and a conformally coated insulated copper wire (0.15 mm diam.) attached to the base of each high-resistance lead.

A custom fixture was used to facilitate alignment and securing of three substrates into the I-beam configuration shown in FIGURE 1. Note that the individual dipoles have been oriented with respect to the probe axis so that their centers are collinear and their axes mutually orthogonal. While in the fixture, the three substrates employed are cemented together with a thin coating of epoxy. The three dimensional I probe is removed from the fixture, and the six copper leads are terminated in a miniature six-prong plug. This assembled unit is inserted into a Lucite® mold, and the probe body is cast in epoxy.

PROBE EVALUATION

Response Patterns

Evaluation of the probe involved several measurements in air, which included individual dipole pattern and polarization, detector dynamic range, frequency response, and probe interaction with microwave fields. Dipole patterns and polarization tests were performed at 2450 MHz. The probe was analyzed in two ways: one involved the use of a near field technique in which the probe was rotated in front of a 6-cm long × 0.7-cm wide slot radiator; the other technique involved a plane wave irradiation technique in an anechoic chamber. The near-field test tended to provide information about the group of dipoles themselves, neglecting the scattering effects from the probe handle and other factors. Near-field testing requires precise spatial control when positioning a probe, because significant variations exist in the field over a few centimeters. A precision probe positioner (FIGURE 3) was used to rotate the probe. It consists of a dielectric arm that can be positioned in the three cylindrical coordinates and has position encoders on each axis. Dipole pattern data were obtained for each dipole, which was aligned with the electric field approximately 12 cm from the slot. The probe was situated such that the dipole under test was directly over the center of rotation of the probe positioner. The dipole axis was placed collinear with the axis of rotation. Rotation of an ideal dipole would produce a

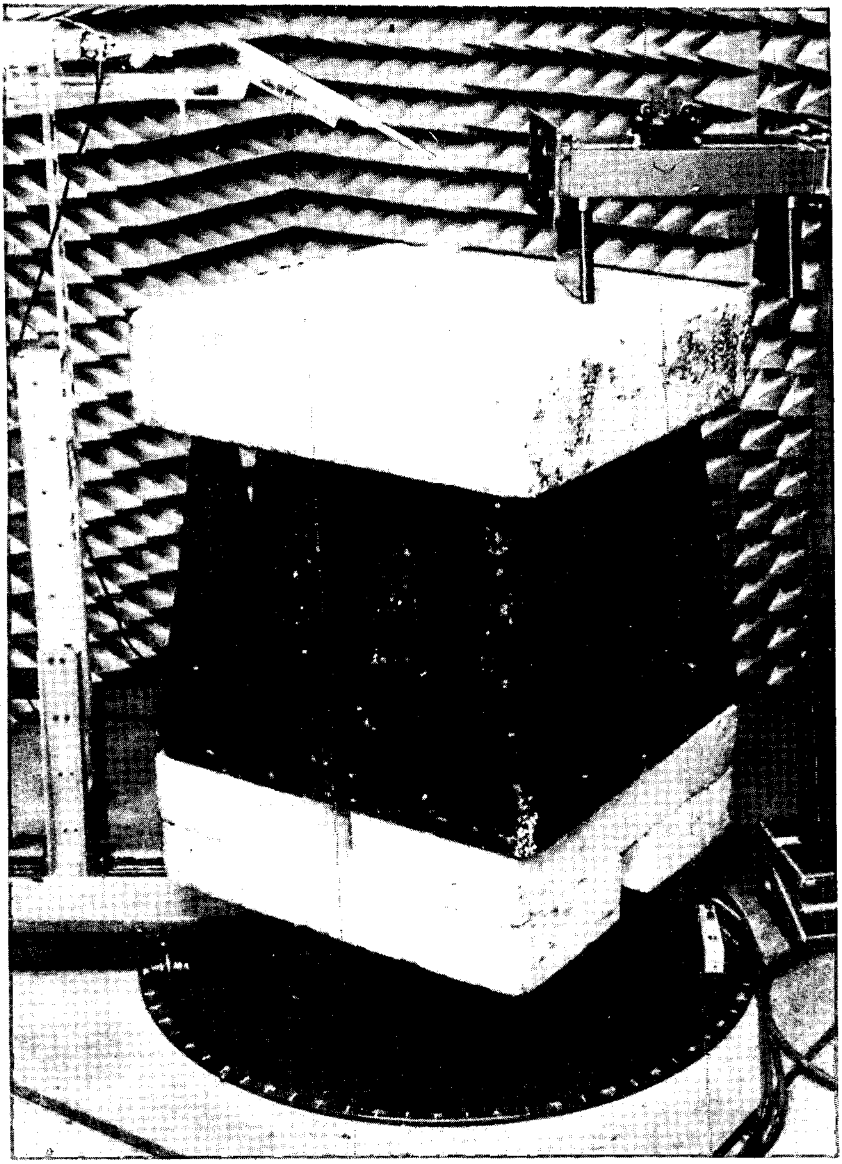

FIGURE 3. Precision probe positioner and slot source.

constant amplitude output under these circumstances. The X, Y, and Z axis dipoles yielded patterns that were constant within 0.83, 0.68, and 0.46 dB, respectively, over 270° of rotation. Further rotation was not possible due to the probe handle's contact with the slot source at angles of ± 135°.

Polarization data were taken for each individual dipole. In this test, both the electric field from the slot source and the dipole under test were placed perpendicular to the rotational axis. The dipole was rotated through the cross-polarized position into alignment with the E field. The X, Y, and Z dipoles all yielded the ideal polarization response, with maximum signal obtained when the dipole was aligned with the E field, and an output that decreased 18.9, 21.5, and more than 30 dB, respectively, for the X, Y, and Z dipoles when cross polarized. The nulls appeared 90° from the maxima, as expected, which indicated no high-impedance lead interaction with the dipoles. This is especially significant for the Z-axis dipole, whose leads are perpendicular to the dipole. Since a deep null occurs when the high-impedance leads are totally aligned with the E field, the lack of lead pickup is clearly demonstrated.

Dynamic Response

Data were obtained with the probe containing standard Schottky diodes. With a 20-MΩ load impedance, the output is highly linear (± 0.2 dB), with increasing power (square-law performance) from 20 to 100 mW/cm^2 (274–614 V/m) with outputs of 18 and 145 mV, respectively, at these levels (FIGURE 4). Below this level, sensitivity decreases with the exposure level in an exponential fashion. With higher load impedances, the square-law region can be extended down slightly but with an increase in background noise. The zero-bias Schottky diode is clearly required at these lower power levels, rather than the incorporation of linearizing electronics. With true square-law performance, the outputs of each axis may be summed to yield the proper sum of squares value for the resultant E-field vector, which is linearly proportional to equivalent plane wave power density.

Frequency Response

The frequency response of the probe was evaluated in an anechoic chamber over the range 915 MHz to 10 GHz. Absolute calibrations were performed at 2.45, 5, and

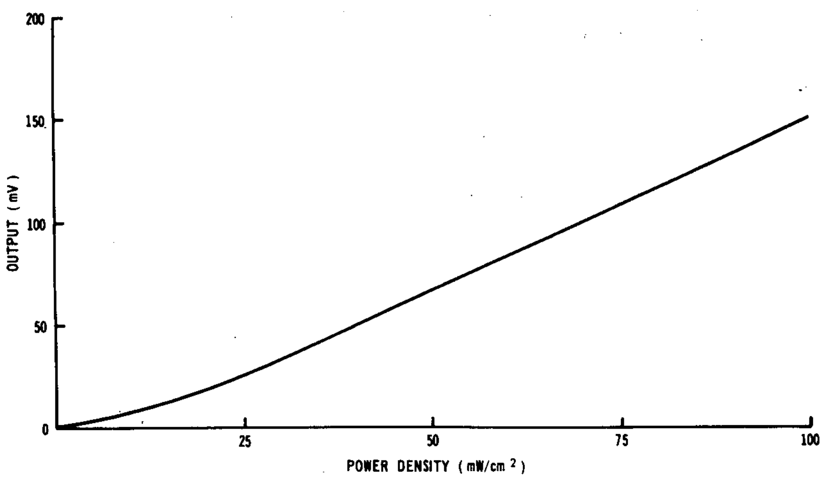

FIGURE 4. Probe dynamic response.

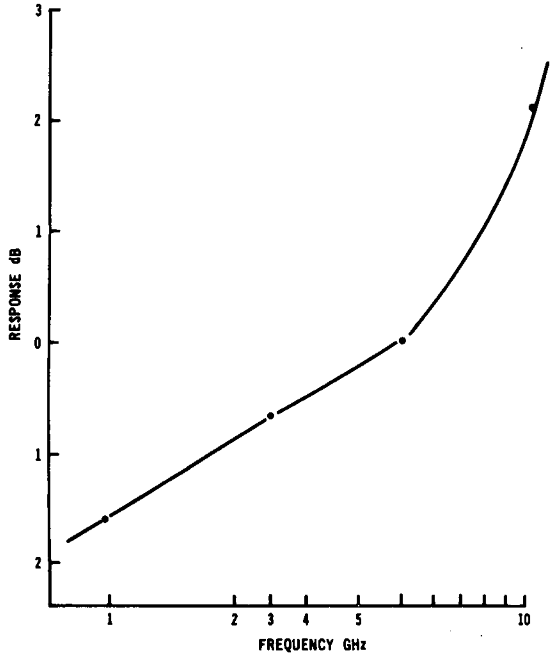

FIGURE 5. Frequency response of a dipole detector assembly.

10 GHz under plane wave irradiation situations (10 mW/cm²). At 915 MHz, a transfer calibration was made at an equivalent power density level of 10 mW/cm² under near-field conditions, with several instruments that were previously calibrated under far-field conditions. The results are illustrated in FIGURE 5. Responses of −1.4 and +2.1 dB were measured for 915 MHz and 10 GHz, respectively, with 5 GHz as a reference level, which thus confirmed the expectations of probe frequency insensitivity. Over the range of output voltages measured, the detector is somewhat nonlinear; it tends to exaggerate the high end of the frequency response curve. That is, a true square-law detector, such as those that will be used in later probes, will yield a flatter frequency response curve.

The increase in sensitivity of the probe at higher frequencies is thought to be caused by the increase in dipole sizes relative to a wavelength and by the consequent increase in antenna radiation resistance relative to the detector forward resistance.

Far-Field Evaluation

The frequency response experiment provided data on other aspects of the device under plane wave irradiation. Cross polarization of the dipole with the electric field yielded a detected signal that was 15–25 dB lower at all frequencies. This indicates that the high-impedance leads were not acting as extraneous antenna elements. The problems of RFI creating offset in the preamplifier that was used to evaluate the probe account for some of the error signal associated with the above cross-polarization test. It was therefore concluded that the high-resistance leads performed properly over the entire operating range of the probe, even when exposed to the same levels as the dipole elements.

PROBE READOUT ELECTRONICS

A high-input impedance dc-coupled differential amplifier is required to observe the millivolt level signals while rejecting common mode interference picked up on the high-impedance leads. The amplifier must be physically stationary with respect to the probe because of the high level of transient noise introduced by the movement of connecting wires between the probe and amplifier. The presence of large reflecting objects (conductive wires or objects with a high dielectric constant) will significantly perturb the field under study. Therefore, high-impedance leads should extend back at least 25 cm to a small (3 cm) metallic cube that contains battery-powered amplifiers. In addition, output signals from the amplifier to a remote site should ideally be transmitted without long conductive wires that would perturb the field, especially when the directions of propagation and polarization of the field cannot be aligned for minimal interaction with leads.

To transmit amplified data without wires, an optical telemeter was developed and fabricated with discrete electronic components. Designed for minimal battery power consumption, the unit contains a differential amplifier, voltage-to-frequency converter, and an infrared light-emitting diode that transmits encoded fm data over a fiber optics link to a receiver several meters away. The system provides an overall accuracy of $\pm$ 2% and is presently under preliminary design in hybrid microcircuit form, so that a 3-cm cube will contain three such telemeters and batteries sufficient for 50 hr of use. FIGURE 6 illustrates the microminiature readout system.

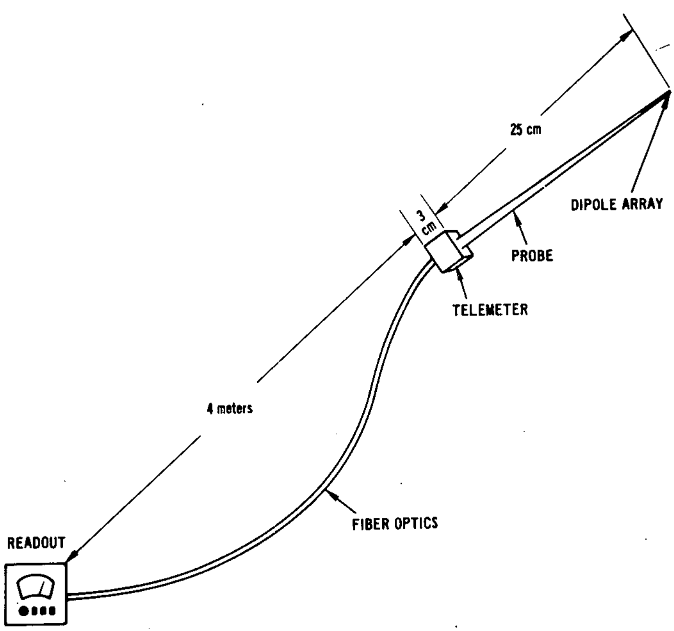

FIGURE 6. Probe and optical telemeter.

Future Plans

The basic probe configuration was found to provide good orthogonality and frequency response. In an effort to further reduce the probe's interaction with the fields under study, materials of lower dielectric constant will be used for the probe substrate and the potting compound in an attempt to more closely match the probe to free space. The high-resistance leads shall be extended to 25 cm in length and will replace the present six copper wires in the base of the probe. The microcircuit telemeter will be firmly attached to the probe base with a locking miniature connector. For the implantable probes, higher dielectric constant materials should be used. These materials can be selected for the particular implantation situation. Calibration of the probe in tissue equivalent dielectric media will be performed with known plane wave irradiation of large thick slabs of the media in which the electric field can be analytically determined. As previously mentioned, the zero-bias detector diode will be incorporated in a prototype probe and, if successful, shall be used in all future probes to improve sensitivity and increase the linearity of the probe at low signal levels. The modifications should yield a probe that fully meets the stated goals of the program.

Acknowledgment

The concept of the colinear dipole center configuration, as applied to the I-beam approach, was developed through discussions with W. Herman, Deputy Branch Chief, Electromagnetics Branch, Bureau of Radiological Health.

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Discussion

Dr. T. C. Rozzell (*Office of Naval Research, Arlington, Va.*): How rigid is the 25-cm tip of the probe and does it have to be rigid? Could the probe be shortened?

Mr. Bassen: The probe should be long to remove the 3-cm metal cube that contains the telemeter from the measurement area. Otherwise, scattering would occur and would distort the field in question. At present, we feel that the handle must be rigid, because we are using a brittle, thin-film high-resistance lead structure. Other high-resistance devices, such as carbon-loaded Teflon®, could be used, but they generate too much noise upon flexing, so I think that the probe must be rigid.

Dr. A. W. Guy: Have you studied the effects of the different tissue dielectric constants on probe impedance? We have performed experiments on uninsulated implanted dipoles and have found that in moving from a material like subcutaneous fat to muscle, a marked change occurs in the source impedance of the dipole. If the dipole is insulated, this change is less of a problem. Have you considered the problem of the probe being imbedded in the optic lens, the vitreous fluid, and various other tissues? Will the reading be independent of the dielectric constant of the surrounding material?

MR. BASSEN: I have looked at this problem in a different way. The wavelength is shortened in a dielectric medium; therefore, the dipole appears in a different relationship to the wavelength, which could then be calculated by standard antenna equations. As a dipole becomes longer, its radiation resistance increases, and therefore I think we are talking about the same phenomenon in two different contexts. We intend to take a very large lossy slab of dielectric medium, irradiate it with a known plane wave in an anechoic chamber, and compute the field at the point where the probe is located. Dr. Cheung of the University of Maryland is performing this calibration within dielectric media.