A BROADBAND, ELECTRIC-FIELD PROBE USING RESISTIVELY TAPERED DIPOLES, 100 kHz-18 GHz

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ABSTRACT

This paper discusses the theoretical, design, fabrication, evaluation, and calibration aspects of a prototype broadband electric-field probe. Its resistively tapered miniature dipole elements allow measurement of electric fields between 1 and 1600 V/m from 1 MHz to 15 GHz, with a flatness of ±2 dB and an isotropic response of ±0.3 dB.

INTRODUCTION

A new prototype transfer-standard electric-field probe has recently been developed at the National Bureau of Standards (NBS). This probe offers a number of significant improvements over conventional electric-field (E-field) probes. The probe features 1) an ultra-wide useful frequency range of 100 kHz-18 GHz; 2) a frequency response flat to within ±2 dB from 1 MHz to 15 GHz; 3) a wide dynamic measurement range covering 1 to 1600 V/m; 4) an isotropic response whose standard deviation (with respect to angle) is within ±0.3 dB; 5) a small probe body which is only 1 cm in diameter and 4 cm long, and 6) a high resistance transmission cable for connecting the probe's outputs to an external metering unit.

The heart of the transfer-standard probe is an 8-mm resistively tapered dipole antenna. The internal resistive loading profile used produces a traveling-wave antenna [1], thereby eliminating any in-band resonances that would normally occur with a metal dipole antenna. The probe utilizes three of these 8-mm resistive dipoles, configured in a mutually orthogonal arrangement, for isotropic reception. A beam-lead, Schottky detector diode shunts each dipole's center gap, thereby providing detection of induced voltages.

DESIGN CONSIDERATIONS FOR A BROADBAND ELECTRIC-FIELD PROBE

The Resistively Tapered Dipole Element

It is well known that a conventional dipole antenna, which essentially supports a standing-wave current distribution, is highly frequency sensitive [2]. Consequently, the useful frequency range of a conventional metal dipole is limited by its natural resonant frequency, which is a direct function of its length. For flat responses to 18 GHz, probes with dipole lengths of 2-3 mm, and even submillimeter dimensions, have been developed at the expense of significantly reduced sensitivity and seriously degraded antenna reception characteristics [3].

As a means of overcoming the severe size limitations imposed by natural dipole resonance, NBS has demonstrated that a traveling-wave dipole antenna can be realized by continuous resistive tapering of the dipole halves. Detailed studies of the characteristics of resistively tapered dipoles have been extensively pursued by the author [4] and other researchers [5]. Basically, it has been shown that if the internal impedance per-unit-length, $Z^i(z)$, as a function of the axial coordinate, z, can be expressed as

$$Z^i(z) = \frac{60\,\psi}{h - |z|} , \qquad (1)$$

then the current distribution, $I_z(z)$, along the linear antenna is that of a traveling wave, i.e.,

$$I_z(z) = \frac{V_0}{60\,\psi\,(1 - j/kh)}\left[1 - \frac{|z|}{h}\right] e^{-jk|z|} . \qquad (2)$$

The symbols have the following meanings: 2h is the dipole's total physical length, k is the wave number, V_0 is the driving voltage, and ψ is given by

$$\psi \cong 2\left[\sinh^{-1}\frac{h}{a} - C(2ka,2kh) - jS(2ka,2kh)\right] + \frac{j}{kh}\left(1 - e^{-j2kh}\right) , \qquad (3)$$

where "a" is the dipole radius, and C(x,y) and S(x,y) are the generalized cosine and sine integrals, respectively.

In the present study of developing a broadband E-field probe for use in the frequency range between 100 kHz and 18 GHz, an 8-mm long dipole was selected for optimizing the sensitivity and the bandwidth of the antenna, while maintaining a reasonably small physical size. The internal impedance per-unit-length required to achieve a traveling-wave antenna is given by eq (1), and can be specifically expressed as

$$Z_\ell = \frac{60 \times 6.34}{4 - \ell}\ \Omega/\text{mm} \quad \text{for } 0 < \ell < 4 \text{ mm} \qquad (4)$$

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for each side of the dipole. Ideally, the required resistive tapering is 95 Ω/mm at the midpoint (ℓ=0 mm) and infinite at the end of the antenna (ℓ=4 mm). To realize such a resistive tapering profile, the antenna is fabricated by photoetching a thin film of tantalum nitride (TaN), which has a resistivity of 9.5 Ω/sq. Each half of the dipole is 4 mm long and varies linearly in width from 0.15 mm at the dipole gap to 0 mm at the dipole tips, as shown in figure 1. Each 8-mm dipole element, its associated high-resistance leads, and the output and diode gold bonding pads were fabricated using thin-film deposition and photoetching techniques, and reside on a 0.25-mm thick aluminum-oxide (Al_2O_3) substrate, as shown in figure 2.

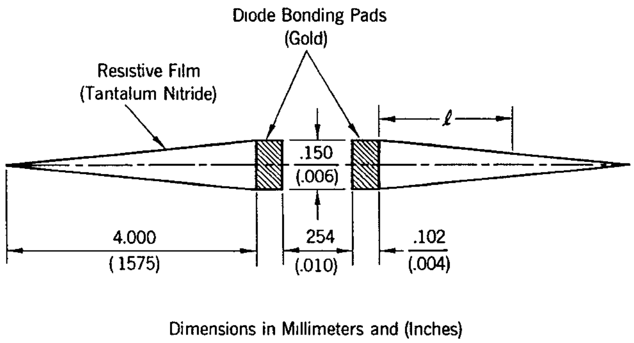

Figure 1. The 8-mm resistively tapered dipole element.

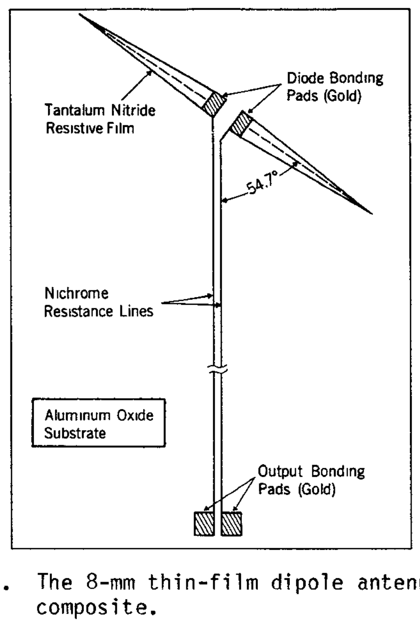

Figure 2. The 8-mm thin-film dipole antenna composite.

Detector Diode Selection

The particular low-barrier Shottky detector, used in the broadband E-field probe, was very carefully selected from the broad range of commercially available beam-lead detector diodes. The predominant characteristics used in the selection were: 1) maximum operating frequency; 2) junction capacitance; 3) junction resistance, and 4) detection sensitivity.

The high-Resistance Thin-Film Transmission Lines

The high-resistance thin-film transmission lines, on each dipole substrate, create a low-pass, distributed filter composed of a highly lossy series inductance with distributed interlead capacitance. This configuration yields an inductance (L) and a capacitance (C) expressed as follows [6]:

$$L = \frac{\mu_0}{\pi} \left[\ell n \left(1 + \frac{d}{a}\right) + \frac{d}{a} \ell n \left(1 + \frac{a}{d}\right)\right] \qquad (5)$$

and

$$C = \frac{\varepsilon_0(\varepsilon_r + 1)}{2} \frac{\pi}{\left[\ell n\left(1 + \frac{d}{a}\right) + \frac{d}{a} \ell n\left(1 + \frac{a}{d}\right)\right]} , \qquad (6)$$

where ε_r is the relative permittivity of the substrate, and ε_0 and μ_0 are permittivity and permeability of the free space, respectively. The attenuation constant of the transmission lines is

$$\alpha \cong \left[\frac{\omega C}{2} \left(\sqrt{R^2 + \omega^2 L} - \omega L\right)\right]^{1/2} \cong \sqrt{\frac{\omega RC}{2}} , \qquad (7)$$

assuming negligible values of shunt conductance and $\omega^2 LC$.

For the 0.025-mm wide, thin-film Nichrome (250 Ω/sq) transmission lines spaced 0.025 mm apart and deposited on an Al_2O_3 substrate (ε_r = 8), the typical inductance and the capacitance are $L = 5.55 \times 10^{-7}$ H/m and $C = 9.02 \times 10^{-11}$ F/m. The 40-mm long transmission lines provide a total resistance (R), a total inductance (L), a total capacitance (C), and a total attenuation (A) of: R = 400 kΩ, $L = 2.22 \times 10^{-8}$ H, $C = 3.61 \times 10^{-12}$ F, and A = 0.67 Np (at 100 kHz).

THEORETICAL ANALYSES FOR THE RESISTIVELY TAPERED DIPOLE WITH A DIODE DETECTOR LOAD

Having previously described the impedance profile for the 8-mm resistively tapered dipole with eq (4), the current distribution along the dipole's length can be calculated by numerically solving the one-dimensional wave equation using the method of moments. The effective length (h_e) and the driving impedance ($R_a - j\frac{1}{\omega Ca}$) of the antenna are determined from its current distribution

$$h_e = \frac{2}{k^2 h} \left(1 - jkh - e^{-jkh}\right) \qquad (8)$$

and

$$R_a - j\frac{1}{\omega Ca} = 60\,\psi \left(1 - \frac{j}{kh}\right), \qquad (9)$$

where the term ψ is previously defined in eq (3).

The Thévenin's equivalent circuit model for the resistively tapered dipole loaded with a diode detector is shown in figure 3. The diode I-V characteristic is given as

$$i = i_s(e^{\alpha V} - 1) \tag{10}$$

where $i_s = 2 \times 10^{-9}$A, and $\alpha = 38\ V^{-1}$. The nonlinear diode junction capacitance (C_j) is given as

$$C_j(V) = \frac{C_j(0)}{(1 - V/V_b)^{1/2}} \tag{11}$$

where $C_j(0) = 0.10$ pF and $V_b = 0.45$ V. The frequency response of the antenna is determined by analyzing the nonlinear circuit model using the Newton-Raphson iteration method (a detailed discussion is given in [1]). The probe's dynamic range characteristics can be relatively easily predicted by solving a first order differential equation. It can be shown [7] that for a small induced voltage (V_i), the output dc voltage (V_0) is

$$V_0 \cong -\frac{\alpha}{4}\left(\frac{V_i}{1 + C_d/C_a}\right)^2 \tag{12}$$

and for large V_i

$$V_0 \cong -\frac{V_i}{1 + C_d/C_a} \tag{13}$$

where C_d is the equivalent total detector diode capacitance. Equation (12) indicates that for small induced rf voltages, the output dc voltage is a square-law function of the induced voltage. On the other hand, eq (13) indicates that for large induced voltages, the output dc voltage is directly proportional to the induced voltage.

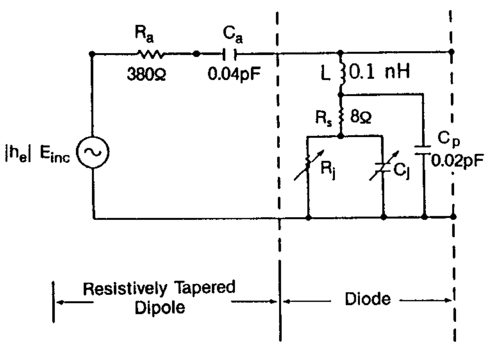

Figure 3. The dipole-diode equivalent circuit model.

EVALUATION OF THE BROADBAND ELECTRIC-FIELD PROBE

The broadband E-field probe prototype was calibrated with respect to the following parameters: 1) frequency response; 2) dynamic range, and 3) probe isotropy. The approach used at NBS for evaluating and calibrating rf radiation monitors is to generate a calculable or "standard" field and then immerse the monitor's probe in this known field. Such standard fields can be established at NBS at any frequency up to 18 GHz with an uncertainty of less than ±1.0 dB.

Figure 4 shows one dipole's dc output voltages as measured at 10 V/m from 100 kHz to 18 GHz.

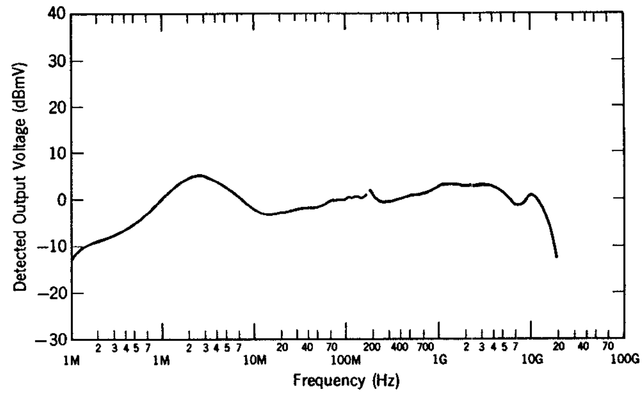

Figure 4. The measured frequency response of one element of the broadband E-field probe at 10V/m.

Probe sensitivity is seen to drop sharply below 1 MHz and beyond 12 GHz. Figure 5 shows the measured plus projected dynamic range of the prototype E-field probe. The detected dc voltage has an accurate square-law response for electric fields of less than 20 V/m. Above 20 V/m, however, the detected dc voltage departs from square law, approaching a linear response near 500 V/m. Since the Schottky diode used has a breakdown voltage of about 4 V, the expected maximum electric field that the probe can measure (without damage) is estimated to be 1.65 KV/m.

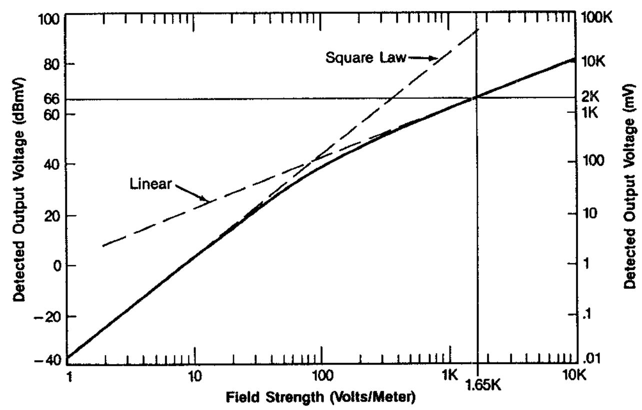

Figure 5. The measured dynamic range of the 8-mm resistive dipole-diode sensing element.

Since the broadband E-field probe was calibrated at 10 V/m, where the detected voltage has a square-law response, it is appropriate to define the transfer function of the probe, in dB, as

$$T_{dB} = 10 \log \frac{V_{max}}{E_{inc}^{2}} \qquad (14)$$

where V_{max} is the maximum dc detected voltage and E_{inc} is the incident electric-field strength. Figure 6 shows the measured transfer functions of each element of the broadband E-field probe.

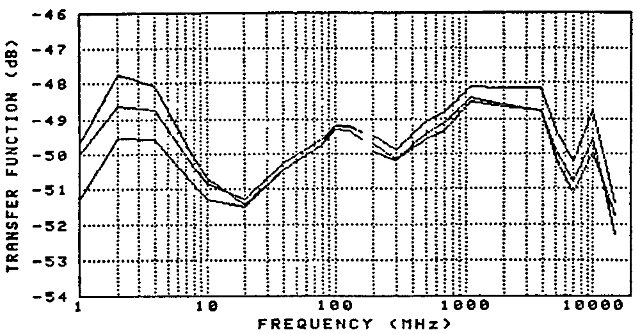

Figure 6. The individual transfer functions of all three dipoles of the probe at 10 V/m.

Probe isotropy is achieved by the mutually orthogonal configuration of the three dipole elements, and its measure can be obtained by correctly combining the three dc detected output voltages. The reception patterns and probe isotropy, illustrated in figure 7, were obtained by aligning the axis of the probe handle such that it made equal angles with the E-vector, the H-vector, and the Poynting vector of a 10 V/m EM field. Measurements were then made and recorded of each dipole's output voltage as the probe was rotated through 360 degrees about the handle's longitudinal axis. It is important to emphasize here that the curves of figure 7 are correct for the probe alignment described and may not represent results obtained using other orientations and/or axes of rotation.

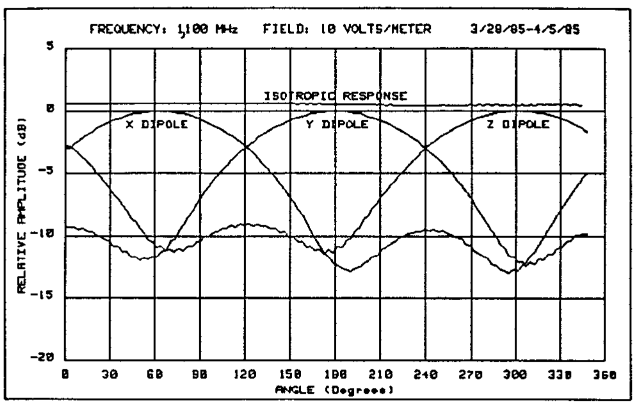

Figure 7. The reception characteristics of the isotropic E-field probe at 1.1 GHz.

CONCLUSIONS

This paper has focused on the theoretical and experimental developmental aspects required to produce and certify a transfer-standard probe. The use of resistive tapering has been shown to yield significant improvements over conventional dipole elements. The use of high-frequency Schottky beam-lead diodes allows the E-field probe to sense fields of 1-1600 V/m over a range of 100 kHz-18 GHz. The mutually orthogonal configuration of the probe's three sensing elements yields a nearly ideal isotropic response (within ±0.3 dB).

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