

OPTIMIZED THERMO-OPTIC ELECTRIC-FIELD PROBES
FOR MICROWAVES AND MILLIMETER WAVES

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Abstract: We report the design and testing of electric-field probes for use at frequencies in the microwave and millimeter-wave range. The probes consist of a resistive element whose temperature rise is measured by an optically sensed thermometer. Design parameters of the resistive element were optimized theoretically, with empirical confirmation. The optimized probe has a flat response above about 13 GHz and can measure fields as small as 17 V/m.

Introduction

Over the past few years, we have been developing electric-field probes for use as transfer standards at frequencies up to 110 GHz. We have already reported calculations and measurements on various candidate designs [1-3]. Related work has been done on similar probes for lower frequencies [4]. On the basis of these earlier theoretical and experimental results and of further calculations, we have chosen an optimal design for the probes. We have now obtained samples of the optimized probe tips and have tested them up to 40 GHz, the limit of our standard-field-generation capability. This paper presents the results of those tests, along with results of some of the calculations used in optimizing the design.

The basic thermo-optic (TO) design uses an optically sensed thermometer [5] to measure the temperature rise of a resistive element exposed to an electric field. The sensor operates by using a pulse of light to excite a small quantity of a phosphorescent material and then measuring the phosphor's decay time, which is temperature dependent. The incident pulse and the light emitted by the phosphor as it decays are transmitted between phosphor and metering unit by an optical fiber. Many different configurations were considered for the resistive element; in the end we settled on a resistive sphere surrounding the temperature sensor. An optimized spherical shell was also tested since our calculations indicated that it could be almost as sensitive as the solid sphere, and it could have better low-frequency behavior. These two configurations for the probe tip are depicted in fig. 1. In both TO probe designs, a second temperature sensor (not shown in fig. 1) is used to measure the ambient temperature, and the difference between the ambient and resistive-element temperatures is a measure of the electric-field intensity.

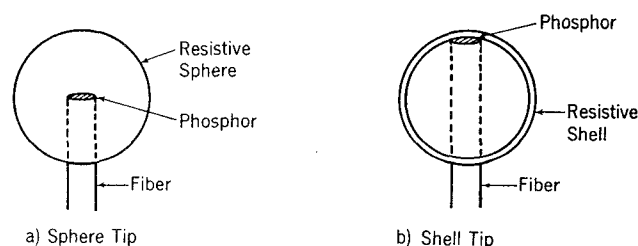


Fig. 1 Resistive element configurations: (a) resistive sphere, (b) spherical shell.

Design Optimization

For each of the candidate resistive configurations, we developed an approximate model which was used to calculate the power absorbed for a given incident field strength and the temperature rise of the phosphor for a given absorbed power. Using this model we then varied parameters such as size and conductivity in order to maximize the temperature rise for a given incident field strength. The calculations themselves are presented elsewhere [2,3]. Here we present the results and discuss some of the general design considerations which emerge from the calculations.

Before considering results for specific designs, we note some general considerations common to them all. The response time of a design is determined by the heat capacity and the thermal conductivity of the material(s) being heated. The sensitivity is determined by a balance between power absorbed by the resistive element and heat lost to the air and to the fiber. The parameters which can be varied for each design are the dimensions and the conductivity. In finding optimal values for these parameters there is a tradeoff between sensitivity and frequency response. (For use as a transfer standard the response time is not a critical consideration.) Because we are considering very resistive materials, resonance effects are suppressed, but the response is still frequency dependent. Larger dimensions for the resistive structure typically result in greater sensitivity but stronger frequency dependence and slower response. For the structures we consider, a radius of 2 or 3 mm generally gives the greatest sensitivity while still maintaining an acceptable frequency response. There is a similar tradeoff in choosing the electrical conductivity. If it is too low, the frequency response is excellent, but the sensitivity is poor. Conversely, a much higher conductivity can yield a good sensitivity (at a given frequency), but the response is frequency dependent. If the conductivity is made too high, both the sensitivity and the frequency response will be poor. The conductivities which are found to be optimal for the configurations we considered are in the range 0.5-50 S/m. This is far below the conductivity of such "resistive" metals as nichrome (about 10^6 S/m) or pure carbon (10^5 S/m for graphite). The resistive materials used in the probe tips discussed below are conducting powders mixed in some dielectric binder.

Figure 1(a) shows the resistive sphere tip design. A solid resistive sphere is formed around the phosphor tip. If the sphere is sufficiently resistive the field can permeate the entire volume. When the entire volume is heated in this manner, much more power can be absorbed than if only a very thin strip or shell were used. This design suffers from the thermal contact between the phosphor and the optical fiber, which constitutes a significant heat sink. The decrease of sensitivity due to contact with the fiber depends on the sphere radius. That is because the rate of heat loss to the fiber is independent of the radius, whereas the heat lost to the air is proportional to the square of the radius. Consequently, the

fraction of the heat lost to the fiber depends on the size of the sphere. For a radius of 1 mm, heat loss to the fiber is the dominant mechanism [2]. For a radius of 3 mm, as considered in this paper, the two mechanisms are comparable, and heat loss to the fiber is not such a serious problem.

The other design we consider in this paper is the shell tip, shown in fig. 1(b). In this design a hollow resistive shell is formed on the end of the temperature sensor so that the fiber pierces the "bottom" of the shell, and the tip of the sensor presses against the inside "top" surface of the shell. This configuration generally results in less absorbed power than the sphere tip, but it also has less thermal contact with, and consequently less heat loss to, the fiber. In practice, this design proves to be somewhat less sensitive than the sphere tip design in our frequency range, but it has better low-frequency characteristics and a shorter response time. It is the preferred design in lower frequency-applications [4].

The response of each of these designs was optimized using model calculations [2,3]. An example of calculation results for the sphere tip design is shown in fig. 2. The temperature rise is plotted as a function of frequency for different values of the sphere radius. The conductivity used for each radius is the optimal value for that radius. It was determined by comparing results for different conductivities at a fixed radius. Based on the calculation results, the optimized parameter values for the sphere tip were chosen to be $r=3$ mm and $\sigma=15$ S/m. For the shell tip the optimal values were $r=2$ mm, $t=0.2$ mm, and $\sigma=10$ S/m, where t is the shell thickness.

On the basis of earlier measurement results, the optimization calculations, and considerations of difficulty of fabrication, we decided that the optimal design would be a sphere tip with a radius of about 3 mm and a conductivity of approximately 15 S/m [2]. Because it is very difficult to measure the conductivity of a highly resistive material at the frequencies of interest (10-110 GHz), we cannot build a probe with exactly the right conductivity. We can,

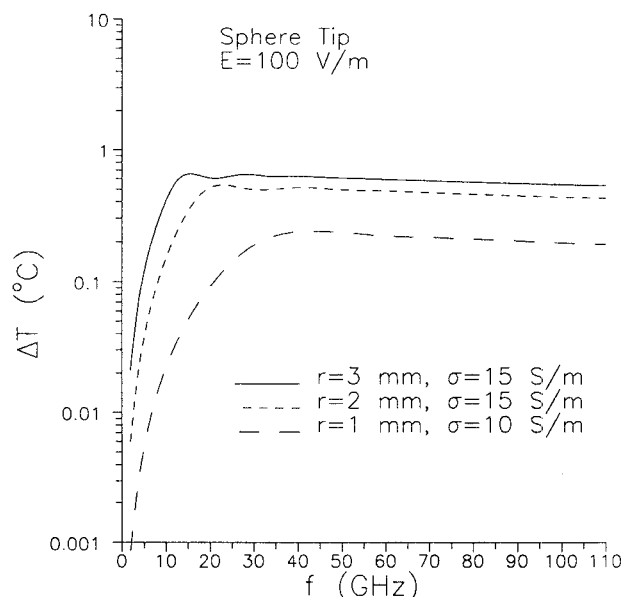


Fig. 2 Comparison of calculated responses for sphere tip with different values of the radius. Conductivity in each case is optimal value for radius.

however, come fairly close. Two different materials were used in the 3-mm probe tips we tested. One of the tips was made of tin oxide (SnO) in a binder of potassium silicate. In this case, the conductivity and relative permeability could be measured up to 18 GHz, and we could fit curves to obtain a reasonable (though not necessarily compelling) extrapolation out to 110 GHz. From this extrapolation, we estimate that the conductivity is in the 2-4 S/m range between 18 and 110 GHz. The other material used to make a sphere tip probe was a mixture of carbon powder and resin. A sample of this material suitable for conductivity measurements could not be fabricated and machined. However, the supplier of the probe tips had experimented with different mixtures to maximize the response for lower frequencies [4]. Therefore, although we do not know that the conductivity is optimal for our frequencies, we are confident that at least it is the correct order of magnitude.

Three probe tips, all of (outer) radius 3 mm, were obtained and tested. Two were of the sphere tip design, one of carbon and the other of tin oxide. The third tip was of the spherical shell design, made of tin oxide. The shell thickness is not known very well, but it is believed to be about 0.2 mm. In what follows the carbon-resin sphere tip will be referred to as the carbon sphere, the tin oxide-potassium silicate sphere tip as the SnO ball, and the tin oxide-potassium silicate spherical shell as the SnO shell.

Measurements

Tests were performed in the NIST anechoic chamber to measure the heating of the tips when exposed to a known electric field. The measurements were all performed in the far field of the transmitting horns, so that the incident field was a single free-space plane wave. In all the measurements, in addition to the sensor used to measure the temperature of the resistive structure, there was a second, uncoated sensor to measure the ambient temperature. The temperature rise is then the difference between the two readings, once they have been corrected for any initial zero-field offset. To shield the sensors from drafts in the anechoic chamber, a thin-walled box was built of closed-cell foam, and both active and ambient sensors were placed within this box for the measurement. In all measurements both sensors were oriented with their fibers perpendicular to the electric field.

The magnitude of the change in the difference between the readings of the two sensors indicates the strength of the applied field. Data acquisition software was written to read the output of the two sensors, average over a number of samples, and compute the statistical uncertainty of the average (s/\sqrt{N}) in the set of samples for each sensor. It also computes the difference in the readings of the two sensors, again obtaining the average and uncertainty for the given number of measurements. In this manner we can monitor the response of the field and ambient sensors individually, as well as their difference. The number of samples we took for a single reading and the statistical uncertainty we were able to achieve depended on the metering unit used. Using the basic metering unit and averaging over sets of 150 samples in all the measurements, we were able to achieve statistical uncertainties of about 0.02°C in the difference between the two sensors. (The time required for a set of 150 measurements was about 21 s.) There is also a new, improved metering unit with a higher sampling rate and less noise than the basic model. With this new metering unit we were able to

take 600 samples in 22 s, and the uncertainty in the resulting temperature measurements was consistently below 0.01°C. Therefore, with the improved unit the minimum detectable temperature rise is 0.02°C, a factor of 2 better (in temperature or power density) than with the basic unit. This represents a rather conservative value for ΔT_{\min} of the new unit. It could probably be decreased further by a more detailed analysis of the statistical uncertainty.

Because we had access to the improved metering unit for a limited time, it was used only in a few tests to determine its sensitivity. All the results presented below were taken with the basic metering unit, averaging over 150 samples for each measurement. In all the measurements the readings were allowed to stabilize within about 0.02°C before the field was turned on, while it was on, and after it was turned off. The field was typically left on between 8 and 12 min. In measuring the frequency dependence of the response, we used the maximum field strength available (200-600 V/m) and the results were adjusted to responses at 100 V/m. This procedure is justified by the excellent linearity of the probes noted below. The response times of the carbon sphere and SnO ball probe tips are about 3 min, whereas the SnO shell has a response time of about 1½ min.

The three probe tips were tested from 12.5 to 40 GHz, and their linearities were measured at 36 GHz. The results are plotted in figs. 3 and 4, which represent the principal results of this paper. Figure 3 shows the frequency response for each of the three probes. The carbon sphere has the greatest sensitivity and has an approximately flat frequency response from 14 GHz up to the highest frequency tested. The SnO ball has less sensitivity, but its frequency response is flat down to at least 12.5 GHz. The SnO shell is almost as sensitive as the SnO ball, but its frequency response is not as nearly constant. The linearities of all three probes are excellent, as shown by comparison to the best-fit straight lines in fig. 4. The error bars in the figure represent the statistical uncertainty in each measurement.

Discussion

Because of its greater sensitivity and good frequency response, we chose the carbon sphere with 3-mm radius as the optimal TO design. From the measured

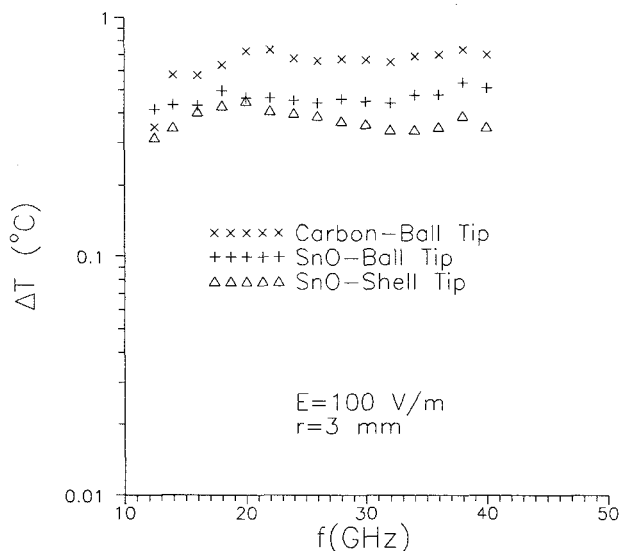


Fig. 3 Frequency response of three probe tips discussed in text.

response of fig. 3 we estimate that the minimum measurable electric field is 17 V/m using the improved metering unit or 24 V/m with the basic unit. If the low-frequency cutoff is an important consideration, the 3-mm SnO ball would be more suitable. Its sensitivity is estimated to be 21 V/m (30 V/m) with the improved (basic) metering unit.

Although the intended operating range of the TO probes extends up to 110 GHz, we have tested them only up to 40 GHz. That is the highest frequency currently available in the NIST anechoic chamber. We can get some idea about how the probes will behave above 40 GHz by comparing the measured data to the calculational results and using the calculations as a guide to the 40-110 GHz range. This extrapolation is complicated somewhat by the fact that we do not know the conductivity of the carbon-resin material in this frequency range. We do know, however, that the conductivity must be close to optimal, which our calculations indicate is 15 S/m. Therefore in fig. 5 we compare the measured data for the 3-mm radius carbon sphere tip to the calculational results for $\sigma=15$ S/m. The agreement is very good, far better than should be expected given the number and magnitude of the approximations made. The important point is that

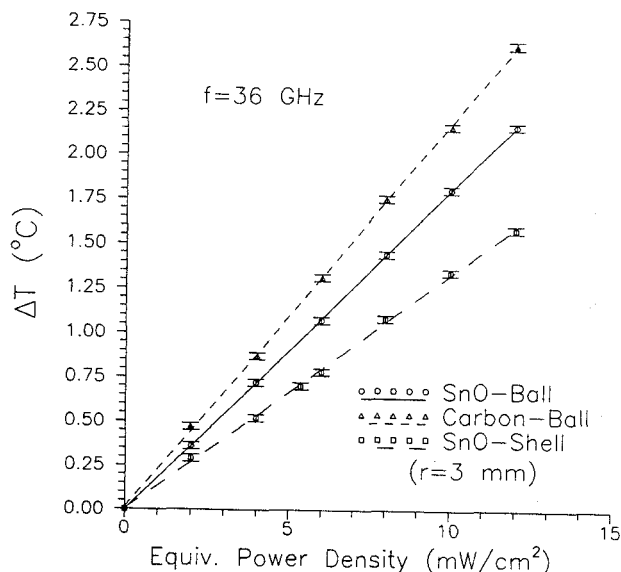


Fig. 4 Linearity of probe tips at 36 GHz.

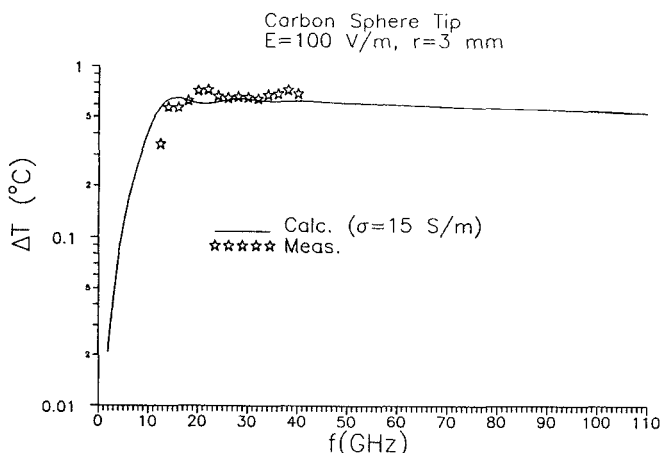


Fig. 5 Comparison of calculated and measured responses of the carbon sphere.

the response is expected to remain quite constant to well beyond 110 GHz, provided that the conductivity does not vary too rapidly.

A similar comparison was performed for the SnO ball probe. In that case we have some information about the conductivity, and so in the calculation we use the values obtained from the extrapolation mentioned above. The agreement between measured and calculated results was good for a probe tip with $r=1.5$ mm, but for the $r=3$ mm tip the measured response was about 30% lower than predicted. This discrepancy is well within the uncertainty of the calculations. Again, the important point is that the response is expected to remain approximately constant to beyond 110 GHz. The only possible problem which we can foresee would be if the conductivity (imaginary part of the dielectric constant) were to exhibit a resonance somewhere in the 18-110 GHz range, but that is not expected for the materials used.

The repeatability of a transfer standard is obviously a critical feature. We did not perform a detailed test of the repeatability. In cases where we did repeat measurements, however, the results agreed within the statistical uncertainty. We also did not test isotropy or stability over long periods of operation.

Summary

This probe was developed for use as a transfer standard, to relate fields generated in one facility to those generated in another. It appears to be very suitable for that purpose up to 40 GHz, the highest frequency we can measure, and we expect its performance to extend to much higher frequencies. The carbon sphere design can measure fields as low as 17 V/m (24 V/m with the basic metering unit) and has an approximately constant response above about 13 GHz. The linearity is excellent, and the repeatability appears to be very good. The isotropy has not yet been tested. The optimization of the design focused on sensitivity and frequency response, especially for millimeter waves. The basic design could also be modified to make the probe suitable for very high power fields or perhaps for hazard meter use. A smaller probe tip would result in less sensitivity,

which would be more appropriate for high power applications. A smaller probe would also have a faster response. The drawback is that the low-frequency cutoff would occur at higher frequency. That and the decreased sensitivity would limit its use as a hazard meter. TO designs for lower frequency applications have been considered in [5]. The fact that the TO designs rely on slow thermal detection limits their use in pulse work. They could measure average powers but could not come close to following pulse shapes.

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