S-1

Millimeter-Wave Material Properties and Measurements

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Abstract

Emerging millimeter-wave (MMW) applications require reliable data on the MMW properties of materials. An overview is given of some of these requirements, the nature and limitations of the available data, the means of obtaining such data, and the progress that is being made in characterizing the MMW properties of materials.

Materials Requirements

Millimeter-wave (MMW) technology has undergone slow growth over the last several decades with periodic bursts of activity. Often in the past these bursts of activity were followed by the realization that critical segments of the technology were not sufficiently mature to support the desired applications. However, in the last few years sufficient progress has been made in most critical areas of MMW technology that some promising applications are now gaining momentum. The Department of Energy fusion program has sought sources that can produce gigawatts of power in the 60 to 100 GHz frequency range for the heating of plasmas. Their efforts indicated that this goal is achievable than they concluded that even higher MMW frequencies are desirable.

A critical bottleneck in the development of such sources is the output vacuum window which must pass very high power densities without failing. The absorption of even extremely small percentages of the high incident power can generate excessive mechanical stresses in the window; this will be true in some other high-power MMW source applications also. Present measurement techniques are at the limits of their accuracy at the levels of the losses of appropriate low-loss materials such as sapphire (power absorption coefficient less than 0.02 cm^{-1}). Verification of the data is a challenging task.

Radar and smart munition radomes can tolerate somewhat larger losses than windows in high-power sources, but verification of these small absorption coefficients can still be challenging. There are no standards for the measurement of the MMW losses of materials. Accurate dielectric constant data are also important for such applications, especially as the wavelengths become smaller and the components become many wavelengths thick. For multiple wavelength thicknesses in components, resonance effects become more dependent on the dielectric constant. However, accurate dielectric constant or optical index data can be relatively easily obtained and verified to high accuracy. Waveguide dielectrics also must be low-loss materials. As the frequency increases into the millimeter range, material losses become a significant factor in overall waveguide losses.

In all the MMW applications requiring low-loss materials, it is desirable to intelligently identify and select materials which provide adequate strength and other properties while minimizing the losses. Unfortunately, relatively little research has been conducted into the basic mechanisms determining the MMW losses of materials. It is often not clear whether intrinsic material loss limits are being confronted, or whether perhaps the troublesome absorption levels can be reduced by further refining or purifying the material.

More effort is needed in obtaining optimum materials for MMW applications. Different mechanisms are likely to dominate in different classes of materials. Degree of crystallinity is a significant factor in some plastics. Multi-phonon processes probably dominate in low-loss single-crystal dielectrics. Free carrier effects are very important in semiconductors. The origins of loss limits in important ceramics such as alumina have several possible explanations not yet resolved.

The successful implementation of nonreciprocal devices, a critical class of components for MMW applications, depends on the availability of suitable ferrite materials. The characterization of MMW ferrites is challenging because of the need to separate the MMW dielectric and magnetic properties. There is reason to believe that systematic errors may have occurred in the past in the attempt to separate these MMW properties.

Although many measurements have been reported on the MMW properties of materials over the years (1), the level of effort has been relatively low, the community has been far flung (both geographically and in journals of publication), and the accuracy of much of the data has been difficult to establish.

Measurement Techniques

Measurement techniques for the determination of the dielectric or optical properties of materials are well established, proven, and employed by a large body of researchers at both the microwave and the far infrared boundaries of the MMW spectral range. However, the microwave waveguide techniques are difficult to extend to the extremely small dimensions of MMW waveguides. The standard optical techniques commonly employed in the far infrared encounter serious diffraction complications as the wavelength increases into the MMW range. Careful adaptations of quasi-optical techniques have resulted in a variety of measurement configurations which have been quite successful (2). Index of refraction measurements to an accuracy of at least four significant figures have been achieved. Power absorption coefficients are difficult to confirm, but accuracies are probably at least two significant figures in some cases.

Unfortunately, quasi-optical techniques in the MMW range require samples having dimensions of many wavelengths. Such sample sizes are sometimes not available--for example in the cases of some MMW ferrites. Therefore, the MMW range requires its own trade-offs of measurement techniques tailored to the wavelengths of interest and the samples available. It does appear that many materials can be studied down to 60 GHz or lower using quasi-optical techniques.

Measurement Accuracy

Various techniques yield MMW measurement values to several significant figures. It is at least as challenging a task to establish the accuracy of these numbers as it is to obtain them in the first place. There are no standards at present for the measurement of the MMW properties of materials. However, there are various approaches which can give some indication of the reliability of the measurements. The indices of refraction of low-loss MMW materials change only very slowly in going from the microwave to the far-infrared region. Interpolations can therefore be made of some materials, such as single-crystal quartz (2), to obtain MMW index "standards" to about four significant figures. Unfortunately, the material losses change substantially in a nonlinear way with frequency and are not easily modeled. Thus, the parameter more difficult to measure is also more difficult to interpolate from microwave and infrared values.

Another approach to achieving credibility in MMW measurement values is to measure the same parameter in the same material by several techniques (3). Ideally, the measurements should all be made on the same sample, but in some cases there is good reason to expect different samples to have the same MMW properties (such as high-quality single-crystal materials). Comparing measurements by different researchers on different samples can sometimes be helpful. This is a useful approach in establishing the MMW losses of materials.

An international sample exchange has been undertaken with this objective in mind. The same set of samples is being measured by 12 different MMW laboratories. The data will be compared and discussed at a wrap-up meeting. The results will be a set of very well characterized "standard" samples and a better appreciation of the limitations and capabilities of various measurement techniques. The results will be shared with the MMW community, and the samples will be available for measurement by other laboratories.

References

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