of weak-bounded excitonic molecules. Otherwise an additional absorption structure due to these complexes would appear in the exciton absorption spectrum as the temperature decreases.

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Waveguide and Open-Resonator Techniques for Submillimeter Waves

R. J. BATT, H. L. BRADLEY, A. DOSWELL, AND D. J. HARRIS

***Abstract*—Resonance techniques at 337 μm (890 GHz) are used to study the performance of modified *H* guide as a low-loss waveguide and of open resonators using spherical mirrors for media characteristic measurement.**

I. INTRODUCTION

THE exploitation of the submillimeter wave region will require the development of a low-mode waveguide of relatively low loss. Consideration of the various guide possibilities has led to *H* guide as the most likely structure [1], [2]. This guide uses the low-loss mode between parallel conducting planes, with a thin dielectric film to concentrate the propagated energy in the required direction. Modifications are required to give a design which combines feasible construction and low loss. Previous measurements of submillimeter waveguide attenuation are confined to loss determination on grossly overmoded rectangular waveguides at 0.85- and 0.65-mm wavelengths. The characteristics of the guide described in this paper have been investigated at 3 cm, 8 mm, and 0.34 mm using a resonance technique, the latter measurements using a HCN laser as source.

Resonance spectra also form the basis for measurement of propagation characteristics of media at 890 GHz by open-resonator techniques. Such methods have been used

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The authors are with the Department of Electrical and Electronic Engineering, Portsmouth Polytechnic, Portsmouth, England.

previously, e.g., by Cullen [3], [4] for the measurement of dielectric properties and scattering characteristics at microwave frequencies, and the characteristics of optical open resonators have also been established [5]. The possibility of measuring atmospheric refractive index, attenuation, dielectric permittivity, and loss angle, and scattering using submillimeter open resonators is being investigated. Initial results on the open-resonator performance and atmospheric characteristics are described.

II. MODIFIED H GUIDE FOR SUBMILLIMETER USE

The basic guide form, together with conductor and dielectric losses, is shown in Fig. 1 for assumed surface resistivity and dielectric loss tangent values. Propagation is possible in the fundamental mode if the plane separation d is greater than $\lambda/2$, with nth order mode propagation possible if $d > n\lambda/2$. The dielectric thickness determines the extension of fields away from the dielectric plane. Theoretical attenuation is low if a thin film of low-loss dielectric is used and the plane separation is sufficient for limited higher order mode propagation. An effective higher order mode filter is then required.

A modified form of H guide is proposed in which the thin dielectric film is supported in channels in the conducting planes as in Fig. 2(a) and (b). The channel is terminated electrically by a short circuit, or by the reactance formed when the dielectric-filled channel becomes nonpropagating at the dielectric edge. The channel length should be such that a low impedance is presented at the plane surface. The outer edges of the plane surfaces can be closed if field magnitudes there are small.

III. MICROWAVE MODEL MEASUREMENTS

The form of guide has been investigated using scaled-up models at 3-cm and 8-mm wavelengths. In each case a length of guide is short circuited at both ends, with power coupled into, and out of, the resonator via small apertures in the end plates. The use of a swept-frequency signal source enables the resonance spectra to be displayed. The width of resonance peaks gives the Q factor of the resonator and hence the attenuation of the guide if resonator end losses are small. Information on the existence of other modes may be obtained from the spectra, and field distributions in a particular mode investigated using a probe technique.

Spectra for guides without channels and plane separations between $\lambda/2$ and λ show a series of equispaced resonances with the correct frequency separation, while guides with plane separations considerably in excess of λ show additional resonances which can be identified for mode order by the probe technique. It has been shown that the guide with dielectric support channels as in Fig. 2 also behaves effectively as a low-loss guide with the additional advantage that the channels can suppress higher order modes. This has been shown convincingly at both 3-cm and 8-mm wavelengths, for plane separations of many wavelengths. A resonance spectrum for the latter

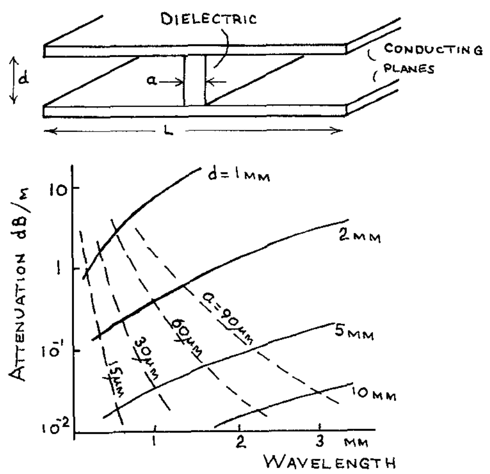
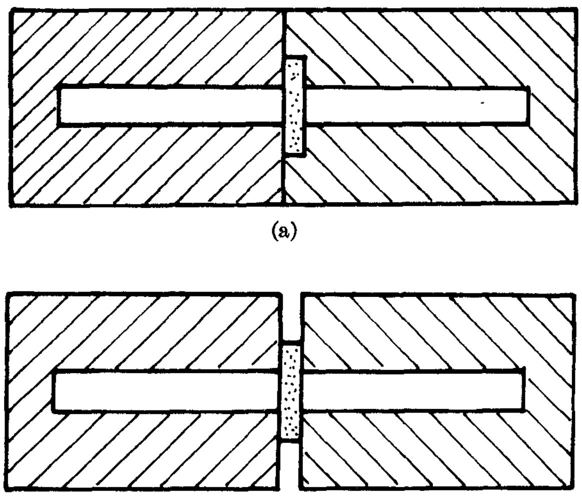


Fig. 1. H-guide basic form and attenuation characteristic.



(a)

(b)

Fig. 2. Practical H-guide cross sections. (a) Short-circuit channel. (b) Open-circuit channel.

wavelength is shown in Fig. 3. Higher order mode suppression is effective over much of the 26–40-GHz frequency range, with additional modes appearing at the ends of the range.

The mode filter operates by virtue of the wall current per unit power propagated along the guide being a minimum for the first order mode, and increasing significantly with increase in mode number. For a channel length such that a small but nonzero impedance is presented at the plane surface, the first order mode will be interrupted less than higher order modes. The effectiveness of the mode filter decreases as the plane separation increases, but it should be noted that the 35-mm plane separation of Fig. 3 would enable up to the eight order mode to be supported in the absence of mode suppression.

Q-factor measurements for a 0.7-mm-thick polythene dielectric gave values up to $9 \cdot 10^3$. This is a factor of 10 below the theoretical idealized prediction and corresponds to an attenuation of approximately 1/3 dB/m, but indicates the low-loss characteristic of the guide, particularly as the design has not been optimized.

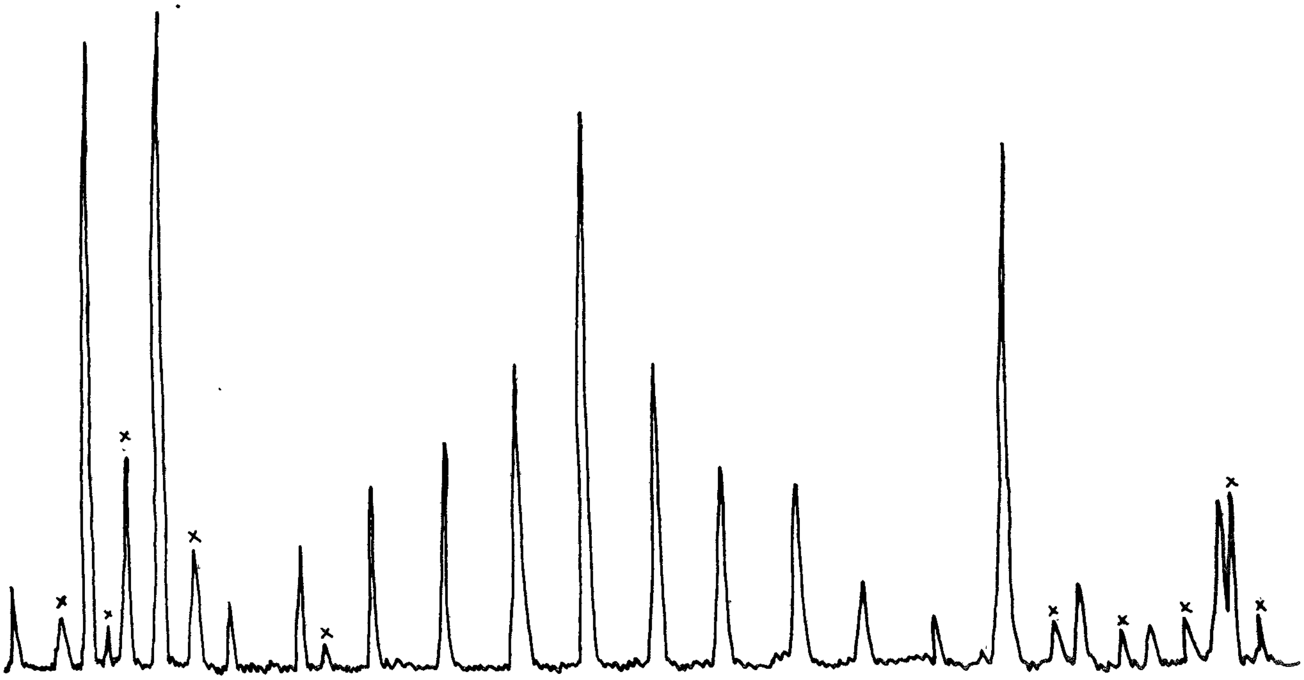


Fig. 3. Waveguide resonance spectrum at 26–40 GHz. ×: higher order modes. Open channel structure guide width 35 mm, i.e., up to eighth order modes possible.

IV. SUBMILLIMETER GUIDE MEASUREMENTS

Lengths of guide have been constructed of the form of Fig. 2(b), for investigation at 890 GHz using a HCN laser. At this wavelength accurate determination of electrical length of the channel is not readily possible, but higher mode suppression is likely for sections of the guide. Initial measurements have been made on the guide with plane separations of 1–3 mm and with Propafilm "*C*" dielectric film 28 μm thick.

Transmission experiments, in which the guide is excited through a 0.01-in-diam aperture centered on the dielectric film have shown that the guide transmits most effectively when the incident wave has the correct plane of polarization for the *H*-guide mode, and that the output power is closely coupled to the dielectric film.

The monochromatic nature of the laser precludes a swept-frequency measurement to obtain resonance spectra. The resonance technique is being applied, however, by closing both ends of the guide and varying the resonator length by temperature change, as in Fig. 4. Initial measurements have recently been obtained, and spectra examples are shown in Fig. 5. The end apertures are 0.01-in in diameter and a temperature variation of 30°C gives more than a half-wavelength change for the 25-cm-long guide section. The length scale is obtained from the known temperature coefficient of brass. These results show that the technique is feasible, thus allowing measurements to be made with various guide designs, materials, etc. The presence of a clearly defined resonance spectrum, which was mirrored on cooling, indicates that true guiding occurred rather than "light pipe" action. For these particular guides, of 2- and 3-mm plane separation, higher order modes also appear to exist. Q factors are about 10^4, corresponding to a guide attenuation of 8 dB/m. This is somewhat greater than prediction, but is nevertheless encouraging at such an early stage of development of the guide.

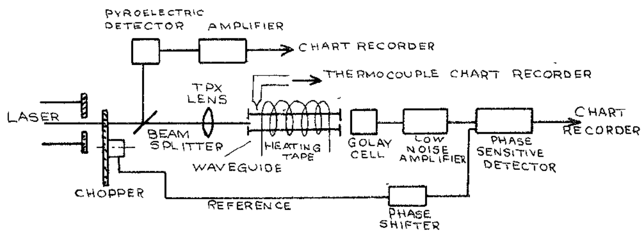


Fig. 4. Submillimeter waveguide measurement system.

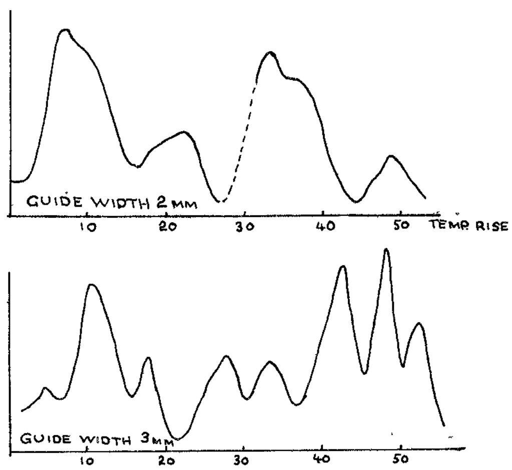


Fig. 5. Waveguide resonance spectra at 890 GHz. Dielectric thickness 28 μm.

V. OPEN RESONATORS

Conventional microwave open resonators consist of two spherical mirrors, or one spherical mirror and one plane mirror, with a microwave source coupled through a small aperture in one mirror and the field intensity sampled by a detector coupled by a second small aperture. The Q factor of the resonator is determined by sweeping the frequency of the source, or alternatively by changing the separation of the mirrors. The Q factor depends upon the total losses in the resonator. Thus the relative permittivity of a sample introduced can be found from the change of frequency or of mirror separation for resonance, and the loss introduced is obtainable from the change of Q factor. The theory for this is well established.

The frequency of a microwave signal, and in particular a shift in frequency, can be measured with great accuracy, and ± 0.25 percent is claimed for relative permittivity measurements at 10 GHz. Measurement of quality factor cannot be made with the same precision, however, and an accuracy of ± 10 percent is claimed for loss-tangent values.

The condition for resonance has been shown [6] to be

$$\frac{4d}{\lambda} = 2q + (1 + m + n)\left[1 - \frac{4}{\pi}\tan^{-1}\frac{R - d}{R + d}\right]$$

where d is the resonator length, λ is the wavelength, R is the spherical mirror radii, and q, m, and n are integers corresponding to the mode designation TEM_{mnq}. The number of field zeros between the mirrors is q, and the number of zeros transverse to the axis in two coordinate directions are m and n. For normal conditions $q \gg m$ or n and the fundamental TEM_{ooq} resonances are separated by a distance of $\lambda/2$. The theoretical change of mirror separation for successive modes can be calculated for each set of experimental conditions.

A submillimeter open resonator would be a most convenient tool if feasible. Overall dimensions would be modest and small diameter mirrors would suffice. While a precise and rigid construction is necessary, the degree of precision is within readily obtainable limits. Since the laser is a fixed frequency source, a variation of mirror separation technique must be used. In order to isolate the input, sampling, and variable separation functions, a folded open-resonator configuration [7] as shown in Fig. 6 is being investigated. The spherical 10-cm-diam mirrors used each have a 1-m radius of curvature, and the overall separation can be adjusted using a translator. The radiation from the HCN laser is mechanically modulated and focused on to a 1-mm input aperture. Sampling is also via a 1-mm aperture in the plane mirror which can be moved in a transverse direction to give variable coupling. Detection is by a pyroelectric detector or Golay cell and phase sensitive amplifier system. The second spherical mirror can be moved continuously by an electromechanical vibrator. The output is then recorded as a function of mirror separation on a chart recorder. The system can be initially lined up using a visible laser.

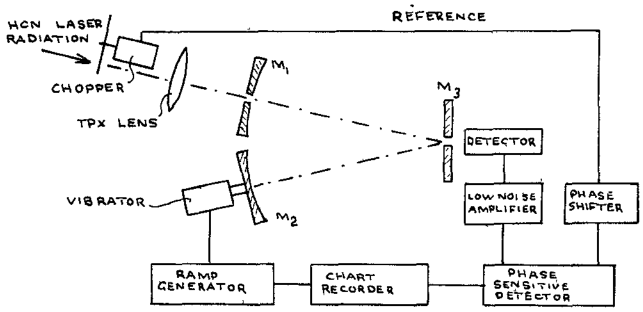


Fig. 6. Open-resonator and measurement technique.

The separation δ of the higher order modes from the fundamental depends upon the path length between spherical mirrors and the wavelength. Putting $\lambda = 337$ μm and $d = 0.63$ m, values of δ for low order modes are

$m + n$	0	1	2	3	4
δ μm	0	60.3	121	181	241.

The mode separation increases from 60.3 to 84.5 μm (i.e., to $\lambda/4$) as d approaches R and all submodes coincide either with the fundamental mode or at the midpoint between these modes.

Beam diameters (to the $1/e$ values) for the $d = 0.63$-m condition are 10.0×10^{-3} and 7.1×10^{-3} m at the spherical and plane mirrors. Diffraction and hole-coupling losses can be estimated, and are found to be negligible and <3 percent, respectively. Reflection losses require a knowledge of surface resistivity at these wavelengths. A figure of 3 percent loss might be taken. These total losses would give a theoretical Q of about 3×10^5 for the empty resonator. Overlap of fundamental resonances will restrict measureable lower Q values to about 5×10^3. The upper limit will be set by the precision, stability, and adjustability of the resonator.

VI. EXPERIMENTAL MEASUREMENTS

Initial adjustment of the mirrors is readily achieved using the visible laser, the input path being lined up with the axis of the laser. Sufficient power is coupled into the detector for measurement with an incident laser power of 1 mW. A series of resonance spectra has been obtained for various mirror separations, and a typical response is shown in Fig. 7. The main TEM_{ooq} resonances can be easily identified, with a separation of $\lambda/2$ as expected. The higher order mode resonances can also be identified and good agreement is obtained with expected positions for the modes. Variation of mirror separation moves the mode positions as predicted by theory. The resonance half-width can be measured, and Q factors for the empty resonator up to 2×10^5 have been achieved. The agreement with calculations is good, bearing in mind the uncertainty of reflection loss values.

Qualitative tests have been made on the effect of introducing dielectric films into the resonator path. It is found that the mirror position for resonance is changed, and the resonance peaks are broadened. Initial measure-

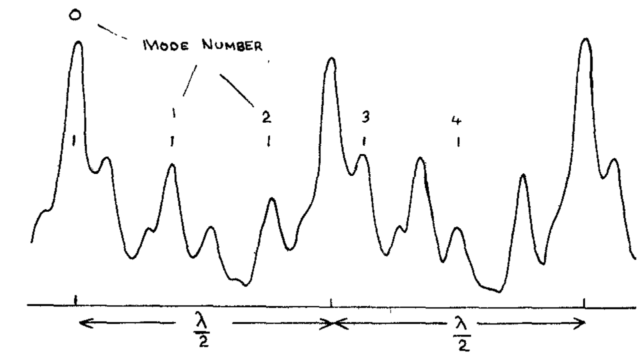


Fig. 7. Open-resonator spectrum showing main and subsidiary mode resonances.

ments on the mirror displacement give agreement to within 10 percent of calculated values using the known permittivity of polythene, and it is clear that careful measurements and appropriate calculations would yield the dielectric properties with an accuracy sufficient for most practical applications.

Attention has been focused mainly on the measurement of atmospheric properties at 890 GHz, and in particular the effect of water vapor on the attenuation and refractive index of air. Fig. 8 illustrates the influence of water vapor content on the Q factor and position of the resonant peaks for a resonator length of 0.63 m. Comparison of the Q factor of the resonator with water vapor against that for a dry atmosphere enables the additional attenuation due to water vapor in the propagation path to be determined. Values of attenuation for relative humidities at 26°C obtained are 23 dB/km at 16 percent, 55 dB/km at 29 percent, and 106 dB/km at 56 percent. High accuracy is not claimed for these measurements, but the provision of higher precision displacement and humidity measurement equipment will enable greater accuracy to be obtained. For comparison, measurements using a long-path technique [8] have yielded an attenuation of (50 ± 5) dB/km at 0°C and saturation vapor pressure. Reduction of our value for 56-percent humidity to similar conditions gives 35 dB/km. The shift in mirror position for resonance on the introduction of water vapor enables the refractive index of moist air to be compared with that of dry air. Our results give a shift of 81 μm in the 0.63-m resonator for a relative humidity change from 10 to 60 percent at 26°C. This corresponds to an increase in refractive index of 12×10^{-5} when the water vapor is introduced. This variation is in contrast to the accepted behavior at optical wavelengths where the refractive index is reduced when water vapor is introduced, but does, however, agree with measurements of refractive index at 337 μm using a plane Fabry–Perot interferometer [9]. The numerical agreement lies within a factor of two. The refinements in technique now being introduced will enable more accurate results to be obtained, and enclosure of the resonator in a vacuum chamber would allow the absolute refractive index to be determined.

No measurements of scatter have been attempted, but our experience with the open resonator at these wavelengths does not indicate any reasons why such measurements should not be feasible.

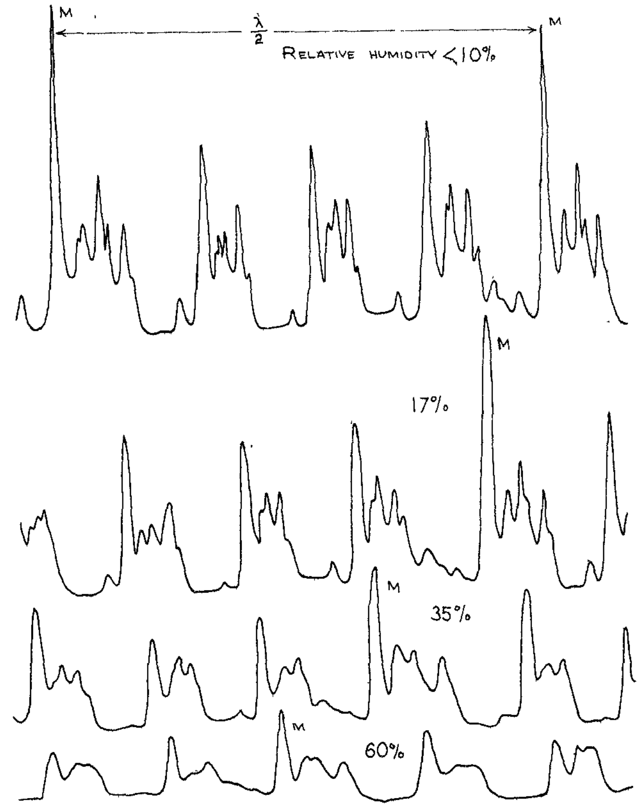


Fig. 8. Variation of resonance spectrum with water vapor content. Resonator length 0.63 m.

VII. CONCLUSIONS

Resonance techniques, using a fixed frequency source and change of resonator length, have been shown to be applicable for the determination of waveguide and open-resonator characteristics in the submillimeter wavelength region.

A guide design for low-loss low-mode transmission at submillimeter wavelengths has been proposed, verified at microwave frequencies, and tested at 890 GHz. Initial measurements indicate that the guide form is promising for the wavelength range.

The open-resonator technique has been shown to be feasible at submillimeter wavelengths. Measurements of atmospheric attenuation and refractive index for varying water vapor content give values which are in general agreement with previous measurements by other methods and refinement of the technique should lead to results of higher accuracy.

ACKNOWLEDGMENT

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Design of a Blackbody Reference Standard for the Submillimeter Region

B. CARLI

***Abstract*—The problems connected with the design of a blackbody reference standard for the submillimeter region are discussed. An emittance of better than 99.9 percent is obtained using a relatively small cavity.**

I. INTRODUCTION

Efficient spectrometric systems [1] and sensitive cooled detectors [2] have been developed in the submillimeter (SM) region, and it is now possible to measure spectra of relatively faint sources with a high signal-to-noise ratio. This state of techniques makes it particularly important to have an efficient blackbody (BB) source to measure the responsivity of detectors and to calibrate the emission of astrophysical objects. The calibration is of basic interest in order to express the signal in terms of the absolute flux of the source. Unfortunately, in the SM region it is not convenient to use the same kind of calibration sources that are used in the adjacent regions: microwave and infrared. In fact, monochromatic calibration sources like those developed for the microwave region are of little use in the SM region where broad-band detectors are used. On the other hand, it is not enough just to scale a BB used at short wavelengths up to SM wavelengths. To verify this we have to premise a few considerations.

Absorption in a BB is obtained with absorbing materials deposited on the surface of the cavity. If we describe the absorbing material as a dielectric of refracting index $\hat{n} = n(1 + i\kappa)$ and thickness l, the attenuation inside the material is expressed by the exponential law $\exp(-4\pi n\kappa l/\lambda)$, and the reflectivity of the first surface (for normal incidence) is $R = ((n-1)^2 + \kappa^2)/((n+1)^2 + \kappa^2)$. The actual absorption of the material is complicated by interference effects, but these two relationships are sufficient to verify that high absorption can be obtained only if the thickness l of the dielectric is comparable with the wavelength λ. So if we scale an infrared BB to longer wavelengths, the thickness of the absorbing layer must be increased. Through the thicker layer a larger gradient of temperature can arise resulting in a less well-defined temperature for the body. This gradient can be reduced only by spreading the flux of radiation emitted or absorbed by the cavity over a larger surface. So while the aperture of the cavity must be increased with the wavelength in order to avoid diffraction effects, the dimensions of the cavity must be increased even faster to minimize the gradient of temperature, leading to very cumbersome cavities for the SM region. In many applications it is extremely important to limit the volume and the weight of the BB, and in general cost and handiness ask for a BB as small as possible.

Thus the problem of designing a BB for the SM region is quite different from that at other wavelengths. The purpose of this paper is to study this problem explicitly. The following points will be discussed:

1) parameters which determine the reflectivity of the cavity;
2) maximization of the absorption in the SM region;

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The author is with the Department of Physics, Queen Mary College, University of London, London, England.