range 5.2×10^{-4}–8.3×10^{-3} Hz. The results have been obtained during a clear night, pointing to the zenith for about 4 h. No excess noise can be observed in the spectrum with respect to the intrinsic noise of the detector.

IV. CONCLUSIONS

According to these preliminary results one may conclude that there is no excess of low frequency noise due to atmospheric fluctuations in the submillimeter wavelengths.

Since the best available detectors optically matched with optimized IR telescopes show an intrinsic noise more than ten times larger than the corresponding photon noise, our results suggest that IR astronomy can gain in the near future about a factor of ten in the minimum detectable signal by developing better detectors (see, for instance, [3, Fig. 5]).

In the high frequency region other measurements are required in order to clarify the existence of special frequencies at which a strong noise excess has been detected.

ACKNOWLEDGMENT

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Submillimeter Spectroradiometers with n-InSb Detectors

A. N. VYSTAVKIN, YU. I. KOLESOV, V. N. LISTVIN, AND A. YA. SMIRNOV

***Abstract*—The optimal characteristics of amplitude splitters for submillimeter radiation beams are determined. Versions of optical schemes with large light gathering power (LGP) utilizing such splitters are proposed. Using them, high sensitivity receiving devices for the 2–0.2-mm waveband region with Fabry–Perot interferometers (FPI) and Michelson interferometers (MI) and n-InSb immersion detectors (spectroradiometers) are constructed.**

I

THE investigation of receiving devices of the short millimeter and submillimeter waveband region using n-InSb detectors cooled with liquid helium [1] have caused the development of various broad-band radiometers [2]–[4] and spectrometers with grating monochromators [5], [6] utilized in radioastronomy and spectroscopy for various purposes. The increase of signal-to-noise ratio of spectral measurement apparatus using such receiving devices is made possible by improving detector sensitivity, thus increasing the light gathering power (LGP)[1] of the spectral scheme. The LGP of n-InSb detectors, especially immersion detectors, is much more than the LGP of submillimeter monochromators. For this reason the first stage of development of receiving devices was the construction of spectroradiometers based on a combination of immersion n-InSb detectors and spectral devices having high LGP of the Fabry–Perot interferometer (FPI) or Michelson interferometer (MI) type. The main results of the corresponding investigation and development are given in this paper.

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[1] We mean that LGP is value $L = \tau U = \tau S\Omega$, where U is the geometric factor of the optical device, S is the operating aperture, τ is the transparency, and Ω is the solid angle of the beam.

II

The advantage of spectroradiometers using the FPI is the compactness of construction and the possibility of the direct recording of spectra [7]. The increasing of LGP of the FPI can be reached either by increasing the operating surface of reflectors or by increasing the beam divergence angle.

The consideration of conditions of optimal matching of the FPI with the n-InSb detector [8] has shown that the divergence beam quality of the FPI $\tilde{Q} = \nu/\Delta\nu$ is connected with parallel beam quality $Q = \pi(R)^{1/2}/(1-R)$, where R is the reflectivity, by the expression

$$1/\tilde{Q}^2 = 1/Q^2 + (\Omega/2\pi)^2. \quad (1)$$

The maximum transparency of the interferometer with the divergence beam is

$$\tau_m = \frac{2\pi\tau_0}{Q\Omega} \arctan \frac{Q\Omega}{2\pi} \quad (2)$$

where τ_0 is the transparency of the ideal FPI which is equal to unity in the absence of absorption by the interferometer reflectors.

The maximum LGP of the FPI at a given value of operating surface corresponds to the maximum of the product $\tau_m \Omega$ and is achievable at

$$\tilde{Q}\Omega/2\pi \simeq 0.76. \tag{3}$$

To realize the required quality $\tilde{Q}$ at the optimal beam solid angle, it is necessary to choose the reflectivity R satisfying the condition

$$Q \simeq 1.52\tilde{Q}. \tag{4}$$

The transparency τ_m at optimal conditions as follows from (2) is 0.73 and the optimal LGP of the interferometer is

$$L \simeq 3.47\tau_0 S/\tilde{Q}. \tag{5}$$

To obtain correct matching of different parts of the optical scheme of the spectroradiometer, the geometrical factors of the different elements of the scheme should be equal. In the opposite case the LGP of the spectroradiometer, and consequently its sensitivity, are determined by the smallest of geometrical factors. The usual receiver with an n-InSb detector without an immersion lens at the input aperture of 45-mm diameter has a divergence angle of incident beam equal to $\pm 6°$ and consequently its geometrical factor is $U_1 = 0.45\ \text{cm}^2\cdot\text{sr}$. The use of a condensor of pure germanium theoretically increases the geometrical factor of the receiver with an n-InSb detector 16 times. But practically speaking, the geometrical factor of the immersion detectors is increased only 6 times and the directional diagram at an aperture of 15 mm in diameter is increased up to $\pm 42°$. The geometrical factor of such a receiver is $U_2 = 2.7\ \text{cm}^2\cdot\text{sr}$.

To realize the LGP of the detector it is necessary to choose parameters of the FPI satisfying the condition

$$S\Omega = U_n \tag{6}$$

where U_n is the geometrical factor of the receiver. According to (3), it involves increasing the surface of interferometer reflectors proportionally to necessary quality. $S \simeq 0.56\tilde{Q}$ for the immersion detector receiver and $S \simeq 0.09\tilde{Q}$ for the receiver without immersion. If one assumes the diameter of operating surface of the FPI reflectors to be equal to 45 mm (usual diameter of lightguides in radiometers with n-InSb detectors) then the condition of optimal matching of the FPI with the immersion detector deteriorates at $Q \gtrsim 28$ and the LGP of the spectroradiometer is determined by the LGP of the FPI at higher qualities.

Since the noise equivalent power (NEP) (P_n) and minimum detectable temperature difference δT of the receiver in the range of frequencies and temperatures satisfying the Rayleigh–Jeans approximation are connected by the relation

$$P_n = 2k\nu^2 \xi \tau U \delta T c \Delta\nu \tag{7}$$

(where k is the Boltzmann constant, c is the light velocity, and ξ is the factor that takes into account modulation curve shape) so temperature sensitivity of the spectroradiometer in the case of equality of geometrical factors of the FPI and the detector is determined by the formula

$$\delta T = \frac{P_n \tilde{Q}}{2\xi k \nu^3 \tau U_m}. \tag{8}$$

This dependence is presented at Fig. 1 (curves 1 and 2). Calculating, it was assumed that lightguides do not have losses and $\tau_0 = 0.73$.

If the LGP of the spectroradiometer is determined by the LGP of the FPI, then it is follows from (5) and (7) that δT changes proportionally to $\tilde{Q}^2$:

$$\delta T = \frac{P_n \tilde{Q}^2}{2\xi k c \nu^3 3.47 \tau_0 S}. \tag{9}$$

This dependence for two values of the surface of reflectors $S_1 = 15.3\ \text{cm}^2$ (diameter is 45 mm) and $S_2 = 63.2\ \text{cm}^2$ (diameter is 90 mm) is presented in Fig. 2 by curves 3 and 4, respectively.

The metallic meshes and gratings [8], [9] are more suitable for constructing reflectors of the submillimeter FPI owing to their optical properties. Usually retuning of filters and scanning over spectrum is carried out by changing the distance between reflectors of the interferometer. During this, the FPI quality varies proportionally to the square of the wavelength which corresponds to the maximum transparency. This makes difficult the interpretation of the spectrum and decreases the operating range of the interferometer. In addition, owing to strict requirements for reflector parallel conditions, this way of retuning makes the design of the device more complicated.

It is known at the same time that in the case of inclined incidence of polarized radiation on thin one-dimensional wire grating, when vector H of the wave is parallel to the grating plane and perpendicular to the wire axes, the declination of incidence direction from the normal one at angle φ affects the value R in the same way as increasing the wavelength $1/\cos\varphi$ times at normal incidence. Thus, if the retuning of the FPI requires rotating it around the axis perpendicular to the grating wires, then the FPI quality will not change because the transparency maximum will shift from λ_0 to $\lambda_{0\varphi} = \lambda_0 \cos\varphi$ as a consequence of variation of the interfering beam's path difference.

Wire gratings made in laboratory conditions by means of simple appliances were used in constructing a tunable FPI with fixed distance between reflectors. The tungsten wire of 50-μm diameter was used for the 400–800-μm waveband region filters. The reflectors of the filters of the 800–1200-μm region were made of copper wire 100 μm in diameter. The measurements of filter characteristics as a function of angle between filter axis and beam axis have shown that for angles from 0 up to 40° the quality of filters of the first type varied from 18 to 14 and the quality of filters of the second type varied from 25 to

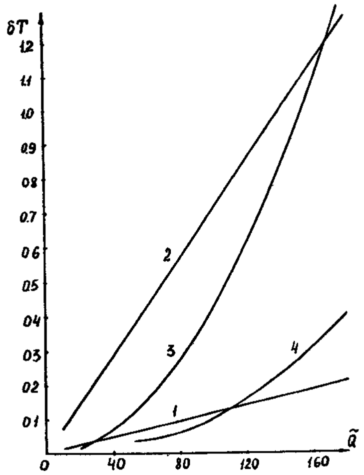

Fig. 1. The dependence of minimum detectable temperature difference δT of the spectroradiometer on the quality of the FPI in divergence beam. Detector NEP $= 10^{-12}$ W/Hz$^{1/2}$, modulation coefficient is 0.5, the frequency corresponding to transparency maximum is 10 cm^{-1}. 1,2—the LGP of the spectroradiometer is determined by the LGP of the detector (1—immersion detector; 2—detector without immersion). 3,4—the LGP is determined by the interferometer (3—diameter 45 mm; 4—diameter 90 mm).

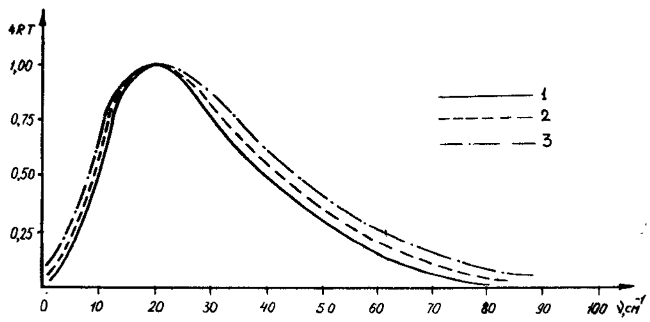

Fig. 2. Frequency dependence of the efficiency of tunnel splitters at incidence angle of radiation on splitter $\varphi = \arcsin [2/(n^2+1)]^{1/2}$. 1—Teflon: $n = 1.5$; $\varphi = 53.5°$. 2—quartz: $n = 2.1$; $\varphi = 37.5°$. 3—germanium: $n = 4$; $\varphi = 20°$. Gap width corresponds to transparency maximum at $\lambda = 500$ μm.

22 at maximum transparency equal to 0.7–0.8 [12]. The value of Q was measured by determining the bandwidth of the apparatus function from the envelope of the interferogram. The transparency of the FPI was determined from the maximum value of convolution of apparatus functions of the FPI and grating spectrometer, characteristics of which were measured earlier [13]. The experience of operating with FPI's of such a construction has shown that they can be used for absolute calibration of submillimeter receiving devices with large LGP and as auxiliary filters for the high resolution Fourier spectrometers.

III

The method of spectral analysis using Fourier transform (Fourier spectroscopy) is developing rapidly now and is finding wider and wider application in submillimeter spectroscopy investigation and radioastronomy [14], [15]. One of the main difficulties during construction of spectroradiometers with MI's (Fourier spectrometers) is the

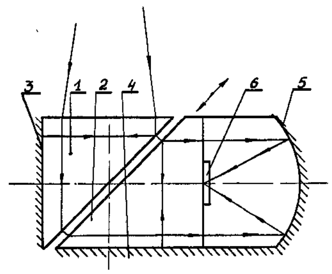

Fig. 3. The scheme of the immersion interferometer. 1,2—prisms; 3,4—flat mirrors; 5—focusing mirror; 6—detector. The path difference is changed by moving prism 2 relative to prism 1.

absence of efficient wide-band splitters of the radiation beam.[2] The investigation of splitters based on tunnel penetration of electromagnetic radiation through the gap between two prisms (tunnel splitters) [16] has shown that the advantage of such splitters consists in the possibility of smooth retuning of the operating waveband region and additional filtering of short wavelength radiation. The characteristics of tunnel splitters of different materials of prisms are presented in Fig. 2. The tunnel splitter allows the construction of the immersion version of the interferometer (Fig. 3), the peculiarities of which are the possibility of the compensation of losses arising owing to reflection from the detector and the possibility of increasing of the maximum solid angle of the beam n^2 times, where n is the refractive index of the material of the prism. The material suitable for construction of the immersion interferometer is pure germanium practically transparent for submillimeter radiation and having a refractive index almost the same as n-InSb.

The immersion interferometer can be used for investigation of submillimeter spectra of low temperature sources, for instance, the radiation of electron gas of semiconductors at helium temperatures or radiation of space background, i.e., in cases when a cooled spectral device is necessary in principle.

When an increase of the LGP of a spectral device is necessary, the dielectric film splitters are convenient. The peculiarity of such splitters is simplicity of design and large LGP connected with the possibility of making a splitter with a large value of operating surface.

The investigation of splitters made of dielectric films and thin plates has shown [17] that it is worthwhile to use thin plates and films with $n \simeq 2.5$–2.8 (quartz, mica) in schemes with angles of incidence of radiation to splitter of the order 20–30°. Splitters made of films with $n \simeq 1.5$–1.7 (mylar, paper) are more efficient placed at Brewster's angle.

As it is known, the action of the splitter made of dielectric film is based on interference phenomena taking place at boundary surfaces between the film and the surrounding medium. Calculating the efficiency of the splitter made

[2] The efficiency of the splitter is characterized by the value $N = 4RT$ where R and T are the reflectivity and the transparency of the splitter.

of material with small absorptivity, one can use formula

$$N = 4R(1 - R) = \frac{16(1 - r)^2 \sin^2 \beta}{[(1 - r)^2 + 4r \sin^2 \beta]^2} \quad (10)$$

which is the consequence of the well-known Airy formula [18]. Here r is Fresnel's energetic reflection coefficient, $\beta = 2\pi\nu dn \cos \theta_t$, θ_t is the wave refraction angle, d is the film thickness, and n is the refractive index of the film material. The efficiency of splitters at various values of r is presented in Fig. 4.

Different requirements for splitter efficiency correspond to different proper measurement problems, but one imagines that characteristics with Fresnel's coefficients from 0.16 to 0.24 presented in Fig. 4 are more suitable for most problems. The efficiency of such splitters in the wide frequency band of each interference maximum is near to the limit value. These splitters are better suited than others for realization of the multiplexity advantage of the Fourier-spectroscopy method.

The dependence of Fresnel's reflection coefficients on angle of incidence allows the variation of the characteristics of the splitter, not only changing the film material but also modifying the interferometer scheme. The efficiency of splitters in interferometers with small angles of incidence of radiation on the splitter ($\theta_i \simeq 20$–$30°$) at $n \simeq 1.5$–1.7 is approximately the same for both polarizations and does not exceed 0.7 ($r_s \simeq r_p \simeq 0.07$ where r_s and r_p are Fresnel's reflection coefficients of s and p polarization, respectively). The efficiency at $n \simeq 2.5$–2.8 is near to optimum for s polarization and slightly less for p polarization and consequently the interferometer polarizes radiation partially.

Optimal efficiency at $\theta = 45°$ (schemes of the interferometers are most compact in this case) is reached at $n \simeq 2.0$–2.6 for s polarization. The efficiency of splitting for p polarization does not exceed 0.6 in this case, i.e., the splitter has strongly pronounced polarizing properties. Optimum value of efficiency for p polarization is reached in such schemes at $n \simeq 3.0$–3.5.

Polarizing properties of splitters made of dielectric films in schemes of interferometers with $\theta > 45°$ are more strongly pronounced. Among schemes of this sort there are schemes of some interest with angles of incidence of radiation on the splitter equal to the Brewster angle in which the influence of p polarization is eliminated. Splitters placed at the Brewster angle have optimum characteristics being made of films with $n \simeq 1.5$–1.7.

During investigation of spectra of randomly polarized radiation the efficiency of the splitter is equal to $(N_s + N_p)/2$. In this case it is reasonable to use the materials with $n \simeq 2.5$–3.0 at smaller angles of incidence of radiation when the efficiencies of splitting of both polarizations are approximately the same or at $\theta_i \simeq 45°$ when decreasing efficiency of splitting of s polarization in the central portion of the operating waveband range is compensated by high efficiency of splitting of p polarization.

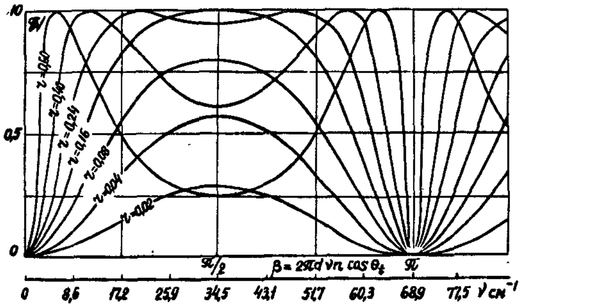

Fig. 4. The efficiency of dielectric film splitters. r—Fresnel's energetic reflection coefficient; d—film thickness; n—refractive index; θ_t—wave refraction angle. The lower scale corresponds to frequency for $n = 1.7$, $d = 50$ μm, incidence angle 61°, and $r = 0.2$.

Our knowledge about dielectric constants of materials in the submillimeter waveband range indicates that there is a wide variety of materials which can be used for splitters. Such materials, for instance, are polyethylen ($n = 1.5$), polyethylenterephtalat (mylar, melinex, lavsan, $n = 1.7$), paper ($n = 1.7$), quartz ($n = 2.3$), mica ($n = 2.5$), and germanium ($n = 4.0$), which have small absorptivity. Technological properties of these materials are important for constructing the splitter with large LGP. A small plane-parallel degree of splitter caused by curvature of surface and inhomogenity of film thickness results in a decrease of the modulation degree of radiation during interferogram recording. It is simpler to obtain a good plane-parallel degree at large operating surface using film materials. Therefore, polyethylenterephtalat films and paper are the most suitable materials for splitters at an aperture with diameter of 150–200 mm. The results of measurements indicate that one can increase the efficiency of splitting in a long wavelength portion of the submillimeter range using the paper with thickness of 200–250 mm.

IV

Results of the research were used in designing of the spectroradiometer for radioastronomical observations [19]. The scheme of the optical part of the spectroradiometer is presented in Fig. 5. The metal focones[3] are used for forming the radiation beam. Collimating input focone with a cone angle of 3° transforms the input beam with a divergence angle of 60° to the output beam with a divergence angle of 12°. Additional focusing of radiation is carried out directly by interferometer reflectors made in the shape of spherical mirrors. The mirrors of reflectors are placed at double focal distance from the output aperture of the collimating focone and input aperture of the receiver at zero position, i.e., when optical lengths of both axial beams in the interferometer are equal.

The moving mirror is moving in a discrete regime by stepping motor along optically polished guides. The 100-μm-thickness polyethylenterephtalat films of 200 μm or more thickness paper are used as the splitters. The splitter

[3] Focone is the focusing cone.

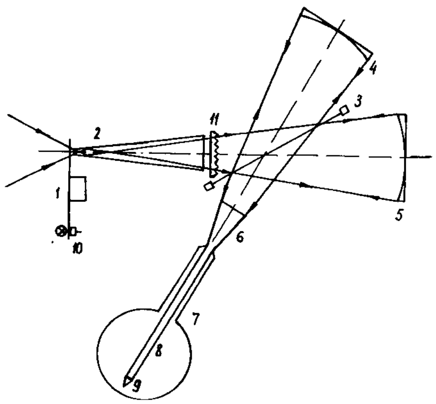

Fig. 5. The scheme of the optical part of the spectroradiometer with modified MI. 1—chopper; 2—collimating focusing cone; 3—splitter; 4—fixed mirror; 5—moving mirror; 6—focusing cone; 7—cryostat; 8—lightguide; 9—detector; 10—reference voltage source; 11—filter.

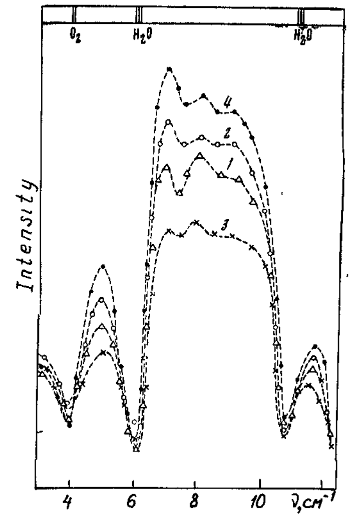

Fig. 6. The spectra of radiation of the sun observed on a clear day of November 20–21, 1972. 1—absolute humidity; $\gamma = 2.73$ gm/m^3; average zenith angle of the sun $\theta = 74°$; air temperature $t = -2°$C. 2—$\gamma = 2.42$ gm/m^3; $\theta = 72°$; $t = -0.6°$C. 3—$\gamma = 2.47$ gm/m^3; $\theta = 75°$; $t = -4.2°$C.

is placed at a 60° angle which is near to the Brewster angle of used materials. Such a scheme has large efficiency and wide operating waveband.

The theoretical limit of resolution of the spectroradiometer determined by the largest path difference of the interfering beams is 0.25 cm^{-1}. Recording of interferograms and interpretation of the spectra of water vapor were made in order to determine the real energetic characteristics of the device and its resolution during investigation of wide spectra. The blackbody at 300 K was used as a radiation source which was placed in front of the chopper. The signal-to-noise ratio during interferogram recording was $\sim 10^3$.

One of the versions of the spectroradiometer together with the submillimeter radiotelescope [6] was used for investigation of submillimeter radiation of the sun at sea level. The spectra obtained are presented in Fig. 6 [20].

V

Modulation by changing the path difference of interfering beams ("intrinsic" or "phase" modulation) has several advantages in comparison with amplitude modulation applied to submillimeter radioastronomy investigations [21]. The main advantages are: 1) the elimination of the dc component of the signal from the interferogram, 2) the increase of the signal-to-noise ratio in calculated spectra, and 3) the decrease of the influence of atmosphere fluctuations. The realization of intrinsic modulation by moving one of the interferometer reflectors with an amplitude of several hundred microns and frequency of the order of 1000 Hz which are necessary using submillimeter n-InSb detectors is difficult because of the absence of systems which are able to produce such mechanical movement. The decrease of frequency of modulation makes worse the sensitivity of the receiver because the spectral density of the noise of n-InSb detectors increases proportionally to $f^{-\beta}$ where $\beta \simeq 0.8$–1.4 up to frequencies of the order of 200 Hz and more rapidly at lower frequencies [1].

One of the possibilities of realization of intrinsic modulation in the submillimeter waveband range with required amplitude and frequency consists in using the transverse oscillations of the membrane mirror surface excited by external periodic force.

The intrinsic modulation by the membrane mirror was tested in the model of the spectroradiometer designed using the scheme of the MI in the Twyman–Green modification. The membrane mirror was made of metallized Lavsan film. The film was stretched on the ring holder with a diameter of 160 mm and attached to the diffuser of the speaker fed by the sinusoidal voltage generator. The excitation of the proper mode of membrane oscillation was obtained by variation of the frequency. The amplitude of oscillations was varied by changing the generator power.

The lock-in detection of signal during measurements was produced at the second harmonic of frequency oscillations of the mirror. Therefore, the frequency doubler was inserted into the circuit of the reference signal. Second harmonic detection has provided the possibility, first, to simplify the identification of zero path difference of interfering beams and, second, to use the standard program of cosine reverse Fourier transform during spectra calculation.

The investigation of the efficiency of the membrane modulator was made using an echelette monochromator. The signal-to-noise ratio in interferograms at intrinsic modulation was 1.8–2 times more than at amplitude modulation by the mechanical disk chopper. The measurements were made using narrow band signals (with resolution of 3–5 percent) in the 400–900 μm-waveband region. The increase of signal-to-noise ratio obtained coincides with theoretical estimation [21].

To verify possibilities of the intrinsic modulation with the membrane mirror in the radioastronomical observations the comparison of intrinsic and amplitude modulation methods was made during registration of the atmosphere radiation. The splitter was made of Lavsan film with a thickness of 100 μm and filtering of short wave radiation was produced by a Teflon 1.5-mm-grating filter. During reception of lower atmosphere radiation the signal-to-noise ratio in interferograms using intrinsic modulation was $\sim 10^4$ which is one order more than using amplitude modulation.

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Balloon-Based Measurements of the Cosmic Background Radiation

JOHN C. MATHER, PAUL L. RICHARDS, AND DAVID P. WOODY

***Abstract*—We have developed and flown a balloon-borne liquid-helium-cooled spectrometer to measure the cosmic background radiation in the 3–18-cm^{-1} region. It features a cooled horn antenna, a polarizing Michelson interferometer, and a germanium bolometer. These design features and the performance of the instrument are discussed.**

I. INTRODUCTION

BIG-BANG cosmology theory and measurements in the microwave- and optical-frequency regions support the idea that the universe is filled with isotropic blackbody radiation with a characteristic temperature of 2.7 K [1].

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Accurate spectral measurements of this radiation are not available for frequencies above the peak of the blackbody spectrum (which occurs at ~ 6 cm^{-1} or $\lambda \approx 1.7$ mm).

II. SPECTROMETER DESIGN AND OPERATION

A far-infrared spectrometer has been developed that can be flown by balloon to an altitude of ~ 40 km to measure this radiation over the frequency range from ~ 3 to ~ 18 cm^{-1}. The principal features of the system are shown in Fig. 1. These include a cooled two-section horn antenna, a cooled polarizing Michelson interferometer [2] used for Fourier spectroscopy, and a germanium bolometer detector. The bolometer is illuminated with a germanium focusing cone. This use of immersion optics [3] increases the throughput by a factor of ≈ 3 without degrading the bolometer responsivity and permits the use of an antireflection coating on the front surface of the germanium cone. The broad-band radiometer sensitivity is