Quasioptical band-rejection filter at 100 GHz

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We describe a tunable Fabry–Perot type filter which has application to radio astronomy in the frequency band 80–110 GHz. The filter causes image sideband suppression when used with a heterodyne spectral line receiver having an intermediate frequency of 4.75 GHz. The transmission loss in the signal sideband is about 0.4 dB, while the image sideband rejection is more than 15 dB; there appears to be little if any problem with scattering or distortion of the antenna radiation pattern.

The tunable quasioptical filter described in this letter is based on the well-known technique of forming a Fabry–Perot interferometer from two partially reflecting metallic grids.[1] Throughout the useful frequency range of the filter the separation, d, of the two grids is approximately[2] related to the wavelength, λ, by the simple formula

$$d = n\lambda/2, \tag{1}$$

where n is an integer.

The filter described herein was specifically designed to reject the image sideband of a heterodyne receiver operating in the frequency range 80–110 GHz. Heterodyne receivers are the basic tools of millimeter-wave radio astronomy,[3] where the most fruitful area of research has been the systematic study of interstellar molecules by means of their line emission. In any such study it is important to provide accurate intensity calibrations, a job made difficult by the double sideband response of such receivers.

The receiver used for the work reported herein was mounted at the secondary focus of the 11 m diam paraboloid of the N.R.A.O.[4] at Kitt Peak, AZ. The antenna was used in a Cassegrainian configuration with an effective focal ratio of $f/D = 13.8$, and the feed horn of the receiver was corrected by a lens yielding an approximately parallel beam ~10 cm in diameter. The filter was mounted ~5 cm from the lens where the beam divergence was negligible. Because of the exacting requirements of its astronomical application, special care was used when designing the filter to prevent loss of signal and to prevent the introduction of distortion of the antenna beam pattern.

In order to achieve the smallest possible transmission of the receiver image sideband, the filter was designed so that the interval between adjacent resonances was equal to 19 GHz or four times the receiver intermediate frequency of 4.75 GHz. The free-spectral range of 19 GHz along with the nominal operating frequency of 100 GHz determine a maximum intergrid spacing of $d = \lambda/2 \approx 8$ mm. This maximal separation is actually used in order to minimize the loss at the receiver signal sideband as we discuss below. In order to ensure that the filter response is not dependent on polarization, care must be taken to operate with the filter approximately perpendicular to the incoming radiation. If the filter is used with a normal angle of incidence, the symmetry of the grids ensures that the filter responds equally to radiation of any polarization. The mechanical design of the filter and the grid parameters adapted are shown in Fig. 1. Laboratory measurements of the image sideband rejection, the tuning characteristics, and the total signal sideband attenuation are presented in Fig. 2.

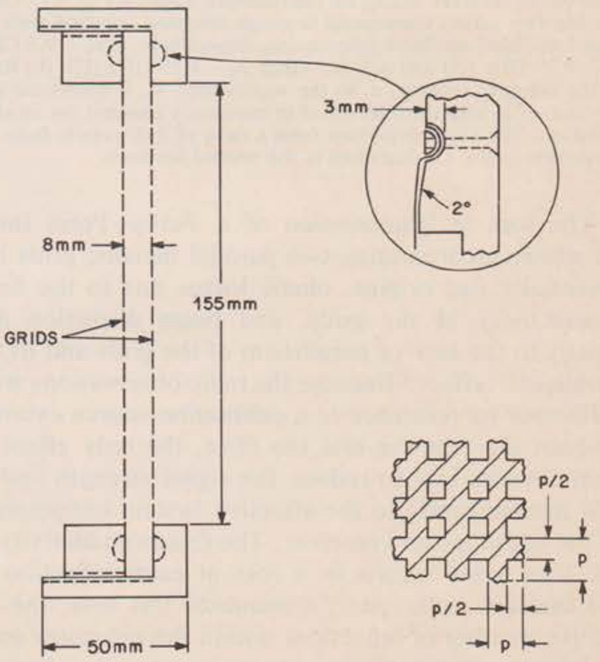

FIG. 1. The assembled filter is shown along with a detail of the grid stretching system and a section of the grid material showing the adapted grid parameters ($p = 2.21$ mm). The two grid supports are threaded, and the intergrid spacing is varied by rotating the supports relative to one another. The grid stretching system consists of a ring of semicircular cross section screwed into a trough. The 2° bevel toward the inside of the trough prevents bulging of the grids.

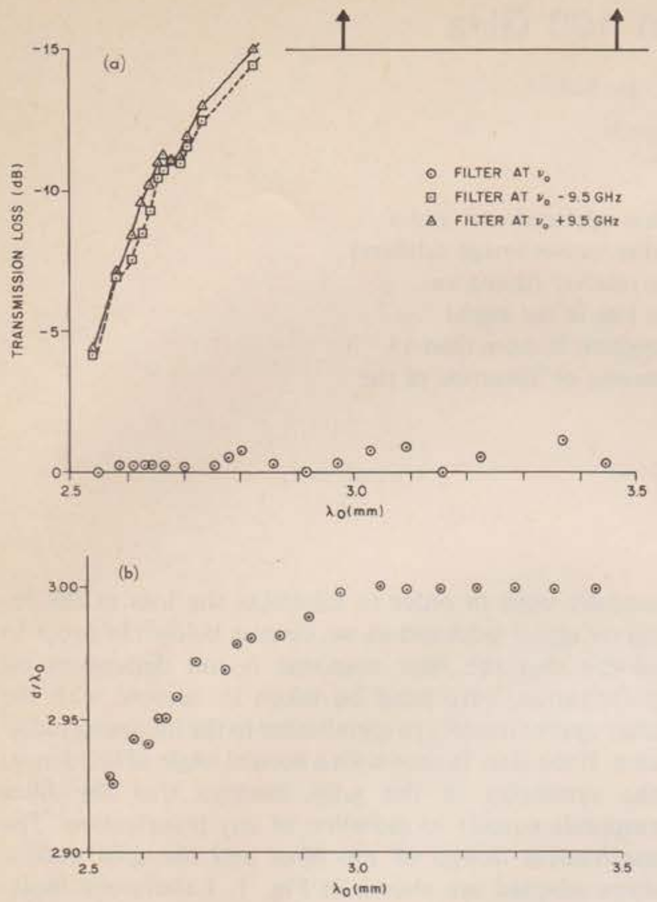

FIG. 2. (a) Transmission loss is presented as a function of wavelength with the filter tuned to maximally transmit the incident radiation (circles), and with the filter tuned to maximally transmit radiation 9.5 GHz above (triangles), and 9.5 GHz below (squares) the incident radiation. Because the filter was used in conjunction with a heterodyne receiver having an intermediate frequency of 4.75 GHz, the last two curves correspond to image sideband rejection with the signal and local oscillator frequencies, respectively, at $\nu_0 + 9.5$ GHz, $\nu_0 + 4.75$ GHz (Δ) and $\nu_0 - 9.5$ GHz, $\nu_0 - 4.75$ GHz (□). (b) Ratio of the intergrid spacing, d, to the wavelength, λ_0, is presented as a function of λ_0 with the filter tuned to maximally transmit the incident radiation. The slight departure from a ratio of 3.00 results from the correction to Eq. (1) described in the second footnote.

The loss in transmission of a Fabry–Perot interferometer incorporating two parallel metallic grids has essentially two origins: ohmic losses due to the finite conductivity of the grids, and beam distortion due chiefly to the lack of parallelism of the grids and to the "walk-off" effect.[5] Because the radio observations were calibrated by reference to a calibration source external to both the receiver and the filter, the only effect of ohmic losses was to reduce the signal strength and to add insignificantly to the effective system temperature of the telescope and receiver. The finite conductivity of the filter grids results in a loss at each reflection of the incident radiation. To minimize this loss, the effective number of reflections within the resonator must be kept to a minimum. In order to maintain an adequate narrow-band response for the filter, it is best to use the largest acceptable intergrid spacing. To minimize the ohmic loss further, it is desirable that the period, p, of the grid be as large as possible, subject to the restriction $p < \lambda$ to avoid the appearance of grating lobes. When p is only slightly smaller than λ, the fine structure of the field generated at one grid decays very slowly as a function of the distance from the grid, and may interact with the fine structure generated at the other grid. This point was of particular concern because the tuning mechanism involves the rotation of one grid with respect to the other. The spurious coupling could also cause a deterioration of the rejection of the receiver image sideband. A ratio p/λ as large as 0.8 was found to work adequately at 110 GHz, and the value $p = 2.21$ mm was used for the filter described. The actual grid was photoetched on a 70 μ thick copper sheet using a computer-generated mask.

Transmission loss in the filter due to beam distortion is a potentially serious problem because of the practical difficulty of measuring the antenna beam pattern. We will discuss two possible sources of scattering and present experimental data which show that the problem is probably not a serious one. One possible source of beam degradation is the possible lack of parallelism of the two grids. Because the machining tolerance in the manufacture of the supporting surfaces of the grids is better than ±0.05 mm, the most likely source of trouble is in ensuring that the grids are everywhere parallel to the supporting surfaces (Fig. 1). Because of the rigidity of the grid material, special care is needed, especially at the edges of the grids (see detail in Fig. 1). Another cause of possible beam degradation is the geometrical walk-off effect[5] which is observed mainly under oblique incidence. We find that this effect is negligible if the incidence angle is less than 3°. A related effect is due to possible divergence of the beam as it passes through the filter. In our application this effect was negligible because of the placement of the filter at the beam waist and because of the high focal ratio available with the Cassegrain system of the telescope.

The effect of beam distortion was checked by a direct astronomical measurement of a well-known

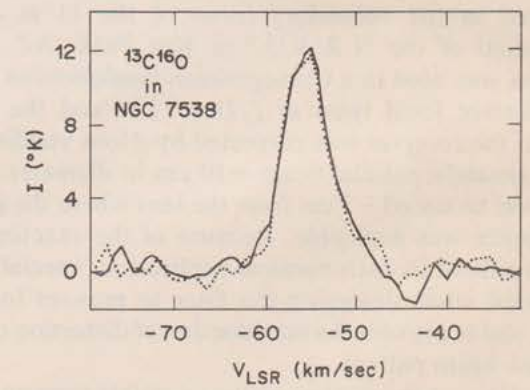

FIG. 3. Emission from the $J = 1$ to $J = 0$ rotational transition of $^{13}C^{16}O$ is presented as a function of velocity relative to the Local Standard of Rest in the direction of the Galactic nebula NGC 7538. Spectra were obtained with (solid line) and without (dotted line) the use of the Fabry–Perot filter. The spectra in either case have been calibrated relative to a calibration source mounted external to the receiver and have been corrected for effects of atmospheric attenuation. The striking similarity of the two spectra demonstrates that the filter introduces no appreciable scattering of the antenna beam pattern outside the 3.5′ radius of the source.

spectral line. We observed emission from the $J = 1$ to $J = 0$ rotational transition of $^{13}C^{16}O$ at 110.201 GHz in the direction of NGC 7538. This source is approximately 7′ in diameter[6] as measured to the radius where its line intensity falls to half its peak intensity. The line intensity was measured both with and without the filter in place, and the calibration in each case was made relative to a noise tube mounted at the Cassegrain subreflector. Thus the apparent line intensity cannot depend on the ohmic losses in the filter which affect the line intensity and the calibration reference equally. However, the apparent line intensity would change if much of the antenna beam, with diffraction-limited angular resolution of about 1′, were spread out beyond the ±3.5′ radius of the source. In Fig. 3 we show the spectra obtained with and without the filter in place and note that the line intensity does not change significantly; more precisely, the line strengths integrated over the total velocity width are 81.2 ± 2.5 K km/sec and 79.1 ± 2.5 K km/sec without and with the filter in place. Thus, to within our experimental limits we detect no degradation of the antenna radiation pattern.

We conclude that for the use with heterodyne millimeter-wave receivers, the Fabry–Perot interference filter described herein provides a useful means for rejecting the receiver image sideband. It combines low signal sideband loss with good image sideband rejection while not apparently affecting the antenna radiation pattern.

[1] R. Ulrich, Infrared Phys. **7**, 37 (1967).
[2] A more precise relation must include the frequency-dependent phase shift $\alpha(\omega)$ which occurs upon reflection from a grid of the particular geometry shown in Fig. 1. Equation (1) then becomes

$$d = (n\lambda/2) - (\alpha\lambda/2\pi).$$

In actual use the filter was tuned by finding the separation, d, yielding the maximum transmission. The effect of $\alpha(\omega)$ on d never amounted to a correction of more than 5% in the range 80 GHz $< \nu <$ 110 GHz. [Fig. 2(b)].
[3] A. A. Penzias and C. A. Burrus, Ann. Rev. Astron. Astrophys. **11**, 51 (1973).
[4] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
[5] J. A. Arnaud, A. A. M. Saleh, and J. T. Ruscio, IEEE Trans. Microwave Theory Tech., **MTT-22** (5), 486 (1974).
[6] H. S. Liszt, Ph.D. thesis (Princeton University, 1973).