The above discussion has assumed that the grating is used in a Littrow tuning configuration, an on-axis arrangement that tends to compress the high-reflectivity region and shift higher order anomalies into this region. Also, problems due to the finite conductivity of the metallic coating of the grating have been neglected, so the analysis applies best at wavelengths longer than 1 μm. It is worth noting that the reflectivity for $E_\parallel$ becomes very high at $\lambda < \lambda_B$, so that for a pulsed laser an even more effective tuning element is possible. For a cw laser, however, the cavity generally has Brewster-angle elements oriented to pass $E_\perp$ which would produce too much loss in operation with $E_\parallel$.

As is well known, Littrow mounted gratings will operate in orders no higher than first at wavelengths such that $\frac{2}{3} d \le \lambda \le 2d$. For our example of the F-center laser with $\lambda_s = 2.2$ μm and $\lambda_l = 3.3$ μm, this implies a range of gratings suitable for use as the groove density between 300 lines/mm and 600 lines/mm. If d is selected so that $\lambda_B = \lambda_s$ and $\lambda_C = \lambda_l$, the groove spacing would be

$$d = \frac{1}{2}(\lambda_s^2 + \lambda_l^2)^{1/2},$$

which is about 500 lines/mm. Such a choice would give the highest reflectivity at the ends of the present tuning range where the gain is the lowest, and a higher output coupling in the middle where the gain is higher.

In Fig. 2 the performance of several rulings is plotted. Two of the rulings have $d^{-1} = 420$ grooves/mm and are blazed at 2.15 μm which puts the second peak at about 4.25 μm. These parameters are close to the condition for minimum threshold deduced above, but provide a somewhat broader tuning range. Because of the groove shape, one ruling gives an output coupling of about 1.5%, while the other one is nearly 12%. The other case in Fig. 2 shows a 400-groove/mm grating selected for high output power operation so that $\lambda_B < \lambda_s$ and $\lambda_C > \lambda_l$, which produces a peak output coupling of about 22%.

The F-center laser has been made to function with each of these gratings, and the thresholds and output powers fit the external reflectivity measurements given in Fig. 2. For example, in the cavity described by German,[2] the grating in Fig. 2 represented by the closed circles produced lasing for all three crystals with external pump powers of less than 100 mW, and the entire tuning range could be covered with a 1-W pump laser. The measured reflectivity of this grating was ≥95% from 2.0 μm to 4.5 μm and clearly fulfills the design objective of a broadband high-reflectivity tuner.

References

1. E. G. Loewen, M. Neviere, and D. Maystre, Appl. Opt. 16, 2711 (1977).
2. K. R. German, Opt. Lett. 4, 68 (1979).

Comparison of Fourier and laser spectroscopy in the far-infrared–submillimeter range

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Successful spectroscopy in the submillimeter–far-infrared (far-IR) region is a difficult task and unconventional methods have commonly been employed in this frequency range.[1] Fourier spectroscopy replaced the then-conventional grating techniques some 15 years ago and still dominates the field. During the transition from grating to Fourier spectroscopy the new method had to prove itself, and several comparison and performance studies were published.[2–7] Recently a new device, the optically pumped far-IR laser, has shown promise as a high-power spectral source. Now, careful comparisons between the established Fourier technique and the new laser spectroscopy are called for. In this Letter we compare state-of-the-art Fourier spectrometers with a recently built laser system by describing measurements made on the same sample, a thin film of the metallic superconductor V_3Si deposited on a sapphire substrate. The very low transmission of this sample provided a demanding test of spectral performance, and the comparison clearly shows the strengths and weaknesses of the two methods.

Two Fourier spectrometers, located at the Ohio State University, were employed in these measurements. A lamellar grating interferometer[8] covered 6–30 cm^{-1}, while a Michelson interferometer[9] was used over 50–200 cm^{-1}. These instruments have effective numerical apertures of $f/1.6$, employ 1.27-cm-diameter light-pipe optics, and use the same type of mercury arc lamp source (General Electric UA-3). In the 6–30-cm^{-1} region this lamp has an apparent color temperature[6] of 4000 K and emits into the aperture $\sim 5 \times 10^{-6}$ W of far-IR power. In the 50–200-cm^{-1} region the color temperature is lower, approximately 1000 K, and the total power delivered is $\sim 2 \times 10^{-4}$ W.

In the lamellar grating interferometer, beam division and interferometric modulation are achieved by two sets of interleaved facets—one fixed and one movable. Because these sets have the same area, the efficiency of this beam splitter is nearly unity. The Michelson interferometer uses a Mylar beam splitter (6.3-μm thick in the present case) and has cat's-eye retroreflectors in the interferometer arms. The beam splitter has a maximum efficiency of 0.6 at 170 cm^{-1} and an average efficiency over 50–200 cm^{-1} of 0.3.

The far-IR radiation was detected by a germanium bolometer operating at 1.2 K. This type of detector[10] typically has a noise equivalent power of 5×10^{-13} W (Hz)$^{-1/2}$ and a responsivity of 10^4 V/W. The detector is in a cryostat which also contains the sample under investigation. The overall efficiency[11] of the Fourier systems, including losses in the windows and long pass filter, is estimated to be 0.008 for the Michelson and 0.02 for the lamellar grating.

The laser spectrometer located at Emory University uses a 20-W cw CO_2 laser to drive a waveguide-type of far-IR cavity. An internal Fabry-Perot interferometer provides line tuning in the cavity, and additional line filtering and wavelength measurement are provided by a second external Fabry-Perot. Some of the far-IR power is introduced into a feedback loop which uses a PZT piezoelectric element to stabilize the CO_2 laser, although some lines lase with sufficient stability that this feedback is not needed. Further stabilization is provided by a source compensation scheme, where the output of a detector following the sample is electronically divided by the output of a detector preceding the sample to give a ratioed quantity with power fluctuations removed. The two detectors are commercial room-temperature Golay cells with typical responsivities of 2×10^6 V/W and noise equivalent powers of 10^{-10} W (Hz)$^{-1/2}$. Standard lock-in amplification of the detector outputs is used with the reference frequency of 11 Hz provided by a mechanical chopper interrupting the far-IR beam. Exact measurements of the laser output power are not available, since there are no well-calibrated far-IR power measuring devices, but estimates based

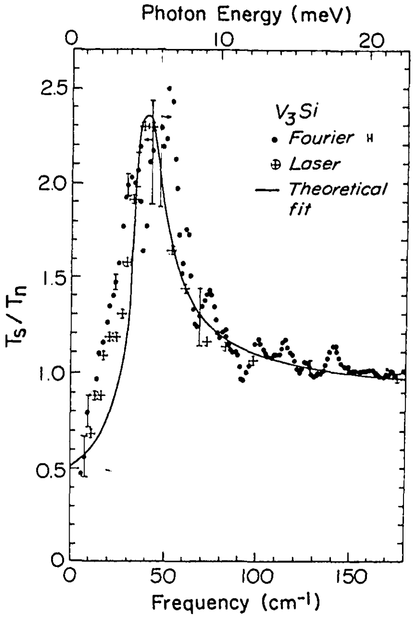

Fig. 1. T_s/T_n for V_3Si as measured by the Fourier spectrometers and by the laser system. Fourier points below 40 cm^{-1} were obtained from the lamellar grating interferometer, while the points above 45 cm^{-1} were obtained with the Michelson interferometer. Error bars are shown for representative Fourier data points. The circles denoting the laser data have diameters equal to the average laser error bar. A detailed discussion of the theoretical fit is given in Ref. 15.

on the detector sensitivity give typical powers between 0.1 mW and 3 mW for the laser lines. Further details of the laser system have been given elsewhere.[12,13]

The sample was rectangular in shape with dimensions of 7 mm by 15 mm. The V_3Si film was 20 nm thick, and the substrate was 0.54 mm thick. Both film and substrate were of excellent optical quality. The film front and back surfaces were smooth and highly reflective with no evidence of inhomogeneity or pinholes. The substrate had well-polished parallel faces. Even before the measurements were made, it was obvious that accurate transmission results would be difficult, since an estimate[14] from the dc resistance (18.4 Ω/□) showed that the low-temperature transmission would be only about 2%.

The far-IR measurements were made to investigate the superconducting behavior of the sample. For such analysis a useful quantity is T_s/T_n, the ratio of the sample transmission in the superconducting state to that in the normal state, where both T_s and T_n are of the order of a few percent. In the laser and in the Fourier systems the sample state was changed from normal to superconducting by varying the sample temperature. In all measurements the normal state temperature was set at 19 K, but the superconducting temperature varied slightly. It was set at 5.5 K at Emory and at 4.2 K at Ohio State. Since both these values are well removed from the transition temperature (15 K in the present specimen), the temperature difference is not expected to affect our results strongly.

The comparative results for T_s/T_n between 6 cm^{-1} and 180 cm^{-1} are shown in Fig. 1, which also shows a theoretical fit to the data for purposes of comparison. The data are in substantial agreement with theory except for the small features at 21–24 cm^{-1} and the low-frequency line shape. The full theoretical analysis is given elsewhere.[15]

The Fourier data were obtained with a resolution of 1.5 cm^{-1} and an integration time of 4 sec/point. The data shown are from the average of six interferograms in both superconducting and normal states with the lamellar grating and the average of three interferograms in both states with the Michelson. In this latter case, measurements were made up to 300 cm^{-1}. The intensity maximum was at ~180 cm^{-1} for the Michelson and at 24 cm^{-1} for the lamellar grating. These frequencies are determined by a number of factors, including the spectral emittance of the source, the beam-splitter efficiency, and the long pass filter employed.

The Fourier data in Fig. 1 have error bars attached to representative points. These points include those near the intensity maxima, those where the intensity is half of and a quarter of these maxima, and the points where the data change from the lamellar grating to the Michelson (near 40 cm^{-1}). The noise levels are calculated as the standard deviations of the individual spectra which were averaged to give the data of Fig. 1. A check on this calculation exists because the sampling interval is about 20% shorter than the maximum allowable value, so the intensity is zero at the high-frequency end of the computed spectrum. The standard deviation of the data in the region gives the noise level, assuming a white-noise spectrum. These two estimates give similar values for the noise level.

For the laser measurements seventeen powerful lines of the many available[13,16] were selected, giving an average frequency spacing of ~10 cm^{-1} between 11.2 cm^{-1} and 175.4 cm^{-1}. Typical lock-in time constants were 0.3 sec. The errors for the laser results, taken as the standard deviations of several measurements, are typically ±2% of the ratio T_s/T_n.

The two sets of data can be compared between 6 cm^{-1} and 30 cm^{-1} and between 50 cm^{-1} and 180 cm^{-1} but not in the peak region 30–50 cm^{-1} where the SNR in the Fourier data was quite low. The agreement between laser and Fourier data between 50 cm^{-1} and 180 cm^{-1} is excellent, with most of the laser points lying at the means of the oscillations appearing in the Fourier data. The low-frequency agreement is also good except at 21–24 cm^{-1}. Here a pronounced shoulder appears in the laser results but not in the Fourier data. The Fourier results do show a slight convexity at the same frequency.

The comparison makes it obvious that there is no serious disparity between results from the older Fourier and the new laser methods. The disagreement at 21–24 cm^{-1} may be due to any of several reasons. It may be related to the small difference in superconducting temperatures, which would be of greatest importance at low frequencies. The most intriguing possibility, however, is that the relatively high laser power may cause some nonlinear effect not as yet understood.

Figure 1 clearly shows where each technique has its strengths. The Fourier method in general can give much higher resolution than is available from the quasi-tunable laser. It would probably be practical to double the number of laser lines shown in the figure to give an average spacing of about 5 cm^{-1}, but a resolution much better than this is unlikely with present techniques. The resolution of the interferometers has been demonstrated to be 0.1 cm^{-1} for the lamellar grating system[8] and 0.05 cm^{-1} for the Michelson system.[9] The lowest laser line was at 11.2 cm^{-1}, whereas the Fourier data extend to 4 cm^{-1}. At comparable resolution, the random errors in the laser data are equal to those in the Fourier data with the advantage that the former were obtained without cooled detectors requiring costly liquid helium. Further proof of the excellent noise performance of the laser system is given by other measurements[15] in a V_3Si film of much greater thickness, where the typical transmission is

0.01%. Here the laser spectrometer gave T_s/T_n with an accuracy only slightly worse than that shown in Fig. 1. The Fourier systems, on the other hand, simply cannot be used with a specimen having this small a transmission.

One feature of the laser system can prove to be either a handicap or an advantage. The narrowness of the laser lines means that interference fringes will appear strongly in cases where the broadband character of the Fourier blackbody source suppresses such effects. A clear advantage of laser spectroscopy is its independence from any computer transformation and analysis of the data and from the related questions of apodization and filtering. On the other hand, the operation of the laser system is at present more complex than that of a Fourier spectrometer. Another measure of the usefulness of the two spectroscopic methods is the actual laboratory time involved in gathering the data shown in the figure. The Fourier results, including setup, data acquisition, and computer data analysis, were obtained in ~20 man hours, while the laser data were obtained in ~60 man hours. While operating, both systems required the attention of one or two researchers.

Our comparisons show that the ideal far-IR–submillimeter spectral source remains elusive. However, the combination of Fourier and laser methods does give the flexibility of choosing the most effective approach for a given spectral measurement problem.

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References

1. For recent historical reviews of far-IR research, see (a) E. D. Palik, J. Opt. Soc. Am. 67, 857 (1977); (b) N. Ginsburg, J. Opt. Soc. Am. 67, 865 (1977); (c) L. Genzel and K. Sakai, J. Opt. Soc. Am. 67, 871 (1977); (d) P. D. Coleman, J. Opt. Soc. Am. 67, 894 (1977).
2. P. L. Richards, J. Opt. Soc. Am 54, 1474 (1964).
3. R. C. Hall, D. Vraback, and J. M. Dowling, Appl. Opt. 5, 1147 (1966).
4. C. H. Perry, R. Geick, and E. F. Young, Appl. Opt. 5, 1171 (1966).
5. R. C. Wheeler and J. C. Hill, J. Opt. Soc. Am. 56, 657 (1966).
6. R. Carro and M. Mattoli, Infrared Phys. 7, 25 (1967).
7. I. G. Nolt, R. D. Kirby, C. D. Lytle,and A. J. Sievers, Appl. Opt. 8, 309 (1969).
8. R. L. Henry and D. B. Tanner, Infrared Phys., 19, 163 (1979). (197x).
9. R. B. Sanderson and H. E. Scott, Appl. Opt. 10, 1097 (1971).
10. F. J. Low, J. Opt. Soc. Am. 51, 1300 (1961).
11. B. Carli, D. H. Martin, E. F. Puplett, and J. E. Harries, J. Opt. Soc. Am. 67, 917 (1977).
12. B. L. Bean and S. Perkowitz, Appl. Opt. 15, 2617 (1976).
13. B. L. Bean and S. Perkowitz, Opt. Lett. 1, 202 (1977).
14. R. G. Glover and M. Tinkham, Phys. Rev. 108, 243 (1957).
15. S. W. McKnight, B. L. Bean, and S. Perkowitz, Phys. Rev. B 19, 1437 (1979).
16. J. J. Gallagher M. D. Blue, B. Bean, and S. Perkowitz, Infrared Phys. 17, 43 (1977).

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