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PROJECT ADMINISTRATION DATA SHEET

☐ ORIGINAL ☐ REVISION NO. ______

Project No. A-3217 DATE 4/13/82

Project Director: Geoff Holah School/Lab EML

Sponsor: NASA; Moffett Field, CA

Type Agreement: Co-op No. NCC2-182

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Sponsor Amount: $12,000

Contracted through: GTRI/~~GIT~~

Cost Sharing:

Title: To Develop Optical Interference Filters for the Wavelength 28 μm to 160 μm

ADMINISTRATIVE DATA

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Defense Priority Rating: None

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RESTRICTIONS

See Attached NASA Supplemental Information Sheet for Additional Requirements.

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GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date: February 21, 1984

Project No. A-3217 — ~~School~~/Lab EML

Includes Subproject No.(s) -----

Project Director(s) Geoff Holah — GTRI / ~~GIT~~

Sponsor NASA; Moffett Field

Title "To Develop Optical Interference Filters for the Wavelength 28mm to 160mm"

Effective Completion Date: 3/31/83 (Performance) 4/30/83 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
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Form OCA 60:1028

A-3217

DEVELOPMENT OF OPTICAL INTERFERENCE FILTERS

FOR THE WAVELENGTH 28 μm to 160 μm

FINAL REPORT

Geoff Holah

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Report for Period April 1, 1982 - March 31, 1983
Contract No. NCC 2-182

Prepared for

NASA - Ames Research Center
Moffett Field, CA

February 9, 1984

INTRODUCTION

Optical filters using interference techniques can be designed with many different transmission or reflection profiles, ranging from very narrow-bandpass through broadbandpass to edge filters. The most widely used fabrication process utilizes multilayer stacks of evaporated dielectrics. The optical thickness of the individual layers is either a quarter-wavelength or a half-wavelength and it is desirable to have alternate layers of high and low refractive index. The dielectrics used must have a sufficiently low absorption coefficient in order to produce an acceptable performance, it must also be possible to evaporate the layers uniformly.

In the visible and near infrared ($< 25\ \mu m$), in general, the above restrictions present no problem; however, for wavelengths greater than 25 μm it becomes difficult to obtain materials which can be evaporated uniformly, have the necessary refractive index different, and have sufficiently low absorption. Additionally, good performance at cryogenic temperatures is difficult due to differential coefficients of thermal expansion. Because of these problems, alternative methods have been attempted in order to fabricate interference filters for these long wavelengths. The method which produces filters with the highest performance and greatest control uses metallic mesh as the reflecting elements of the interference filters. Such filters have found application for wavelengths longer than 50 μm where performances similar to that of dielectric filters in the visible have been achieved. However, success of this technique has been restricted to long wavelengths; furthermore, low temperature performance has not been completely reliable. This latter restriction is particularly important in the application to astronomical observations where systems cooling is essential.

This program represents an effort to study one possible method of reducing the working wavelengths of mesh filters and, at the same time, improving low temperature performance.

INTERFERENCE FILTER BASIC DESIGN CONCEPTS

Whatever the method of producing interference filters, dielectrics or metallic mesh, the basic design features are the same and will be briefly reviewed here. Further details can be found in review articles.

It has been shown that all interference filters can be represented by two reflective surfaces, as shown in Figure 1. After summing the multiply-reflected and then transmitted beams, the transmission through the surfaces can be written:

$$T(\omega) = \frac{T_1(\omega)\, T_2(\omega)}{(1-R(\omega))^2} \qquad \frac{1}{1 + \frac{4R(\omega)}{(1-R(\omega))^2} \sin^2 \beta}$$

where $T_1(\omega)$ and $T_2(\omega)$ are the frequency-dependent transmissions of the two surfaces

$R(\omega) = \sqrt{R_1(\omega)\, R_2(\omega)}$, where $R_1(\omega)$ and $R_2(\omega)$ are the frequency-dependent reflectivities of the two surfaces.

and $\beta = \frac{2\pi}{\lambda} d$, where λ is the wavelength of the incident light and d is the optical separation of the surfaces.

Using equation 1 it can be shown that a bandpass filter is produced when $p\lambda = 2d$ (where p is an integer 1, 2, 3,...); usually such filters work in first order, i.e. $\phi = 1$. Whenever the optical separation of the surfaces is a quarter-wave thickness, then an edge filter is produced. Whether the edge filter is a high-pass or low-pass depends upon the exact form of $T_1(\omega)$, $T_2(\omega)$, $R_1(\omega)$, and $R_2(\omega)$.

Since this program is solely concerned with bandpass filters, no more reference will be made to edge filters. From the preceeding brief discussion, it is clear that in order to produce a bandpass filter at say 28 µm, two reflecting surfaces separated by an optical thickness of 14 µm or some integral muliiple thereof are required.

METALLIC MESH AS THE REFLECTING SURFACES

Having established a design basis, it is then necessary to devise a means of fabricating the filters. Although the operational wavelength of the filter is determined by the optical separation of the two reflective surfaces, the performance of the filter is determined by the flatness of the components and the reflectivity of the surfaces. In multilayer dielectric filters, the flatness is usually excellent since the homogeneity of the successive layers can be controlled by good quality evaporation using rotating sources and substrates. The reflectivity of the dielectric multilayer reflective surface is achieved by having many quarter-wave stacks on each side of the half-wave. Dielectric multilayer filters can be made quite well up to 20 μm; however, at longer wavelengths, absorption due to lattice vibrations and/or free-carriers becomes significant. Furthermore, it becomes increasingly difficult to evaporate the relatively thick layers at these longer wavelengths with the same homogeneity and cohesion found at the short wavelength. Accordingly, metallic mesh has been used to fabricate long wavelength interference filters.

Metallic mesh exists in two complementary forms which are shown in Figure 1.a together with their optical properties. Briefly, inductive mesh, holes in metal foil, has a transmission maximum when the wavelength is equal to the periodicity, g. The transmission falls at longer wavelengths, eventually becoming completely reflecting. The transmission and reflection are complementary. Capacitative mesh, metal squares (which need a substrate), has a transmission minimum for $\lambda = g$ and the transmission increases to long wavelength. A full discussion of metallic mesh interference filters is given elsewhere. Since only bandpass filters are considered here, then the only type of mesh needed is inductive.

From a consideration of the optical properties, it can be seen that any desired reflectivity can be chosen at any wavelength by the appropriate choice of mesh geometry. Having chosen the appropriate mesh geometry, the problem remains as to how to accurately space the meshes with sufficient parallelism. For filters beyond 50 μm, it is possible to use either annular metal shim spacers or a spaceless technique introduced previously. However, it is difficult to use these processes to produce filters with good low temperature performance. Also, these processes do not readily lend themselves for use at shorter wavelengths due to the difficulty of ensuring the two surfaces are parallel. As a rough rule of thumb, it is necessary for the two surfaces to parallel to approximately $\lambda/40$. In order to attempt to solve the low temperature problem and spacing problem, it was proposed to investigate the possibility of fabricating metallic mesh on each side of an optically-prepared transparent spacer.

The steps associated with this possibility can be determined to be:

1. Choice of substrate.
2. Optical quality of finished substrate.
3. Fabrication of metallic mesh on substrate faces.
4. Test of final component.
5. Evaluation.

CHOICE OF SUBSTRATE

The primary requirement on the substrate is that it be highly transparent at the wavelength of interest. Absorption has two effects; first of all, it reduces the overall transmission level and secondly, since the beams reflected within the substrate are being attenuated, the number of reflections each beam makes is decreased which, if too drastic, can decrease the finesse of the filter, thus leading to a broadening of the filter spectral profile.

It is also necessary that the substrate be optically polished on both sides and that the sides be as parallel as possible. Consideration of these parameters led to the possible choice of quartz as the substrates for wavelengths beyond 50 μm and KRS-5 as the shorter wavelength substrate.

As mentioned in the introduction, the optical separation of the two reflecting surfaces has to be a half-wavelength or some multiple. Usually, a half-wavelength separation is used. However, for wavelengths of interest less than 100 μm, this means physical thickness significantly less than 50 μm. It proved impossible to buy such thicknesses in any material, although a sample supply of 50 μm quartz discs were obtained. The need to use thicker substrates ($\geq$ 1mm, for a diameter of 25mm) meant that significant absorption may still be evident. The performance of the filter is determined by the parallelism of the surfaces as well as the reflectivity. In the case of the dielectric spaced filters discussed here, this means that the performance of the filter will be conically dependent.

An effort was made to fabricate some quartz substrates in house. Material used for oscillators was obtained, typically 500 μm thick and one inch square, which had a ground finish on both sides. After prolonged polishing using cerium oxide as an abrasive, a reasonably good finish, at least by infrared standards, was obtained as shown in the step-profile curve in Figure 2. However, this technique did not produce parallel sided substrates. These substrates were used to test other stages in the mesh fabrication process.

It was clear that without extensive precision polishing equipment, it was not going to be possible to produce substrates sufficiently parallel and, at the same time, sufficiently thin.

The preparation of these quartz substrates took place prior to the delivery of the commercial quartz and KRS-5 substrates. The oscillator quartz enabled us to gain valuable experience in the production of metallic mesh arrays on substrates.

PRODUCTION OF METALLIC MESH

As discussed earlier, inductive meshes are needed to fabricate narrow-bandpass filters. The technique decided upon to fabricate these inductive meshes was to deposit a film of metal onto the surface and then use a photo-etching process with a free-standing inductive mesh as the mask.

Initially, aluminum was deposited through evaporation but this proved difficult to obtain good thickness control. It was then decided to use r.f. sputtering techniques. Aluminum is not the easiest metal to sputter, and so finally a two stage process involving chromium and gold was evolved. In this procedure, a thin (300 Å) film of Cr was first sputtered, followed by 2000 Å of Au. This multilayer was repeated on the other side. After the substrate had been coated on both sides, it was mounted on a Si wafer to make handling easier, (this was particularly important for the 50 μm thick substrates). The wafer was then placed on a vacuum chuck spinner and 1350J photoresist spun on at 6000 r.p.m. This is then baked at 95°C for 30 minutes. Exposure took place by placing the inductive mask of the appropriate size over the substrate and placing in a mask aligner; the exposure took 5 sec. This was followed by a 20s develop in AZ developer. Following a rinse in deionized water and being blown dry in N_2, the substrate was baked at 110°C for 30 minutes.

The Au was etched in 50:50 Aqua-Regia -- water heated to 65°C for 2½ to 3 minutes. The resist was then stripped with acetone. The Cr was removed and the substrate rinsed and dried.

The substrate was removed and cleaned by first cleaning in hot trichloro-ethylene, followed by a methanol rinse and N_2 drying. Then the substrate was subjected to a plasma strip for 15 minutes at 300 watts and final removal of the substrate from the wafer was achieved by hot trichloroethylene, methanol rinse and nitrogen drying. This procedure is repeated for the other side.

The results of this process are shown in the microphotographs of the Figures 3-8 . Also included are the results of fabricating capacitative mesh. Together they demonstrate that good quality metallic mesh structures can be fabricated using a sputter/photoetching process. Meshes have been produced with periodicities ranging from 25 μm to over 100 μm.

The main objective was to produce double-sided meshes,and some are shown in Figures 9-12 which also include some capacitative meshes. These photomicrographs clearly indicate that good meshes can be fabricated on both sides of a solid dielectric.

These results were very encouraging, especially when it is realized that for most of these samples, the substrate is 50 μm thick quartz with a diameter of 6mm.

The optical performance of these filters is discussed in the next section.

OPTICAL DATA ON DOUBLE-SIDED INDUCTIVE AND CAPACITATIVE MESHES

Spectra has been obtained using a Fourier Transform spectrometer. Measurements have been taken on both inductive and capacitative mesh filters.

Figure 13 shows the spectrum of a double-capacitative mesh with periodicity 42 μm. For this filter, a very thin plastic (Mylar) substrate was used. Figure13 shows that a low-frequency pass shape has been obtained but with poor rejection in the stop region. This is to be expected with only a two-element, low-pass filter. The advantage of a flexible plastic substrate is that the performance will not degrade with temperature. Figure 14 shows a double capacitative filter using 90 μm periodicity meshes and with the same plastic substrate as the previous filter. This filter has a far better shape and, in fact, could be used as a lowpass filter if perfect rejection is not required.

The Fourier transform spectrometer used for the above measurements was situated at Emory University. It proved necessary to establish this capability, since many delays occurred with the N.A.S.A. Ames Fourier Transform Spectrometer.

Low pass filters are much more forgiving than bandpass filters, with respect to parallelism of the surfaces. This is demonstrated quite clearly in Figure 15 which shows the spectrum obtained on a bandpass filter using a 50 µm thick quartz substrate and with 50 µm periodicity inductive meshes. In terms of quality of processing, this filter represents the best component achieved under this program. Although the spectral resolution of the spectrometer was only 4 cm^{-1}, it is clear that good bandpass performance was not achieved. Structure is seen in the spectrum which can be attributed to interference effects, but the overall performance is poor.

This was a very disappointing result, but not unexpected. It is clearly very difficult to produce solid substrates for metallic mesh filters which have sufficient parallelism. In addition, since the largest size of quartz (the hardest material studied) at a thickness of 50 µm was on the order of 6mm, there is also a serious size limitation.

CONCLUSIONS

1. Thin, parallel, transparent substrates essentially impossible to obtain.
2. High quality photo fabrication of both inductive and capacitative meshes on a variety of substrates demonstrated.
3. Reasonably good low frequency pass filters using just two capacitative meshes can be fabricated using Mylar substrates.
4. Bandpass filters for wavelengths below 200 µm have not been fabricated due to lack of a parallelism of sufaces.

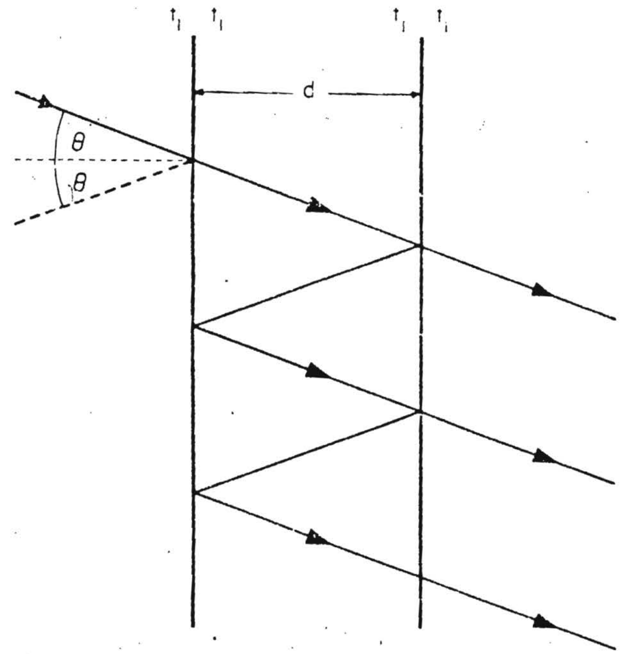

Fig. 1(a). Schematic representation of interference due to two reflecting surfaces.

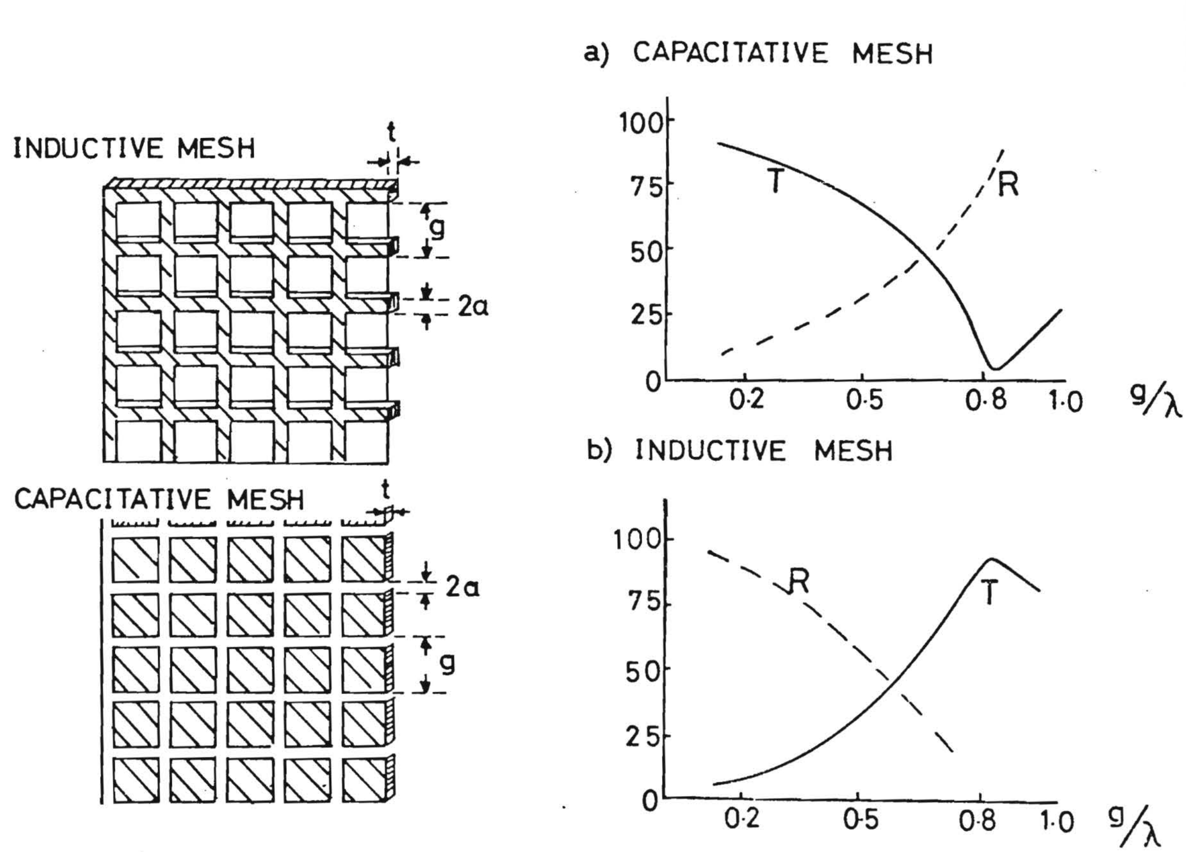

Fig. 1.(b). Structure and Optical Properties of Metallic Mesh

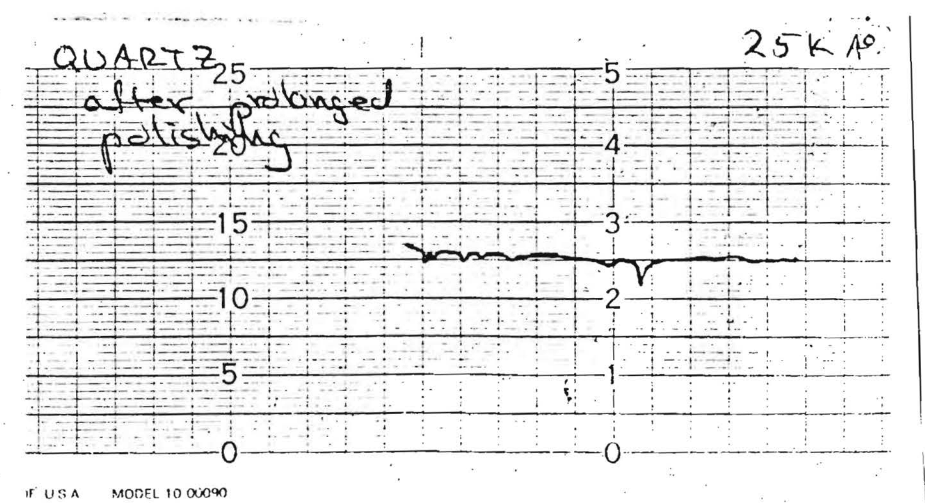

Fig. 2. Step profile of uniformity of polished quartz substrate 25 kÅ full scale.

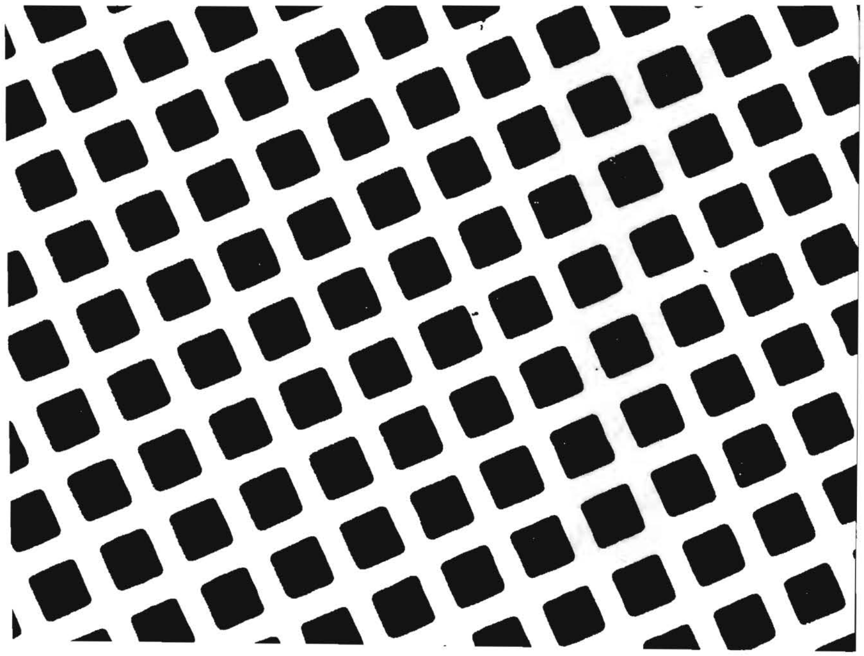

Fig. 3. 50 μm periodicity inductive mesh, 1000Å thick metal

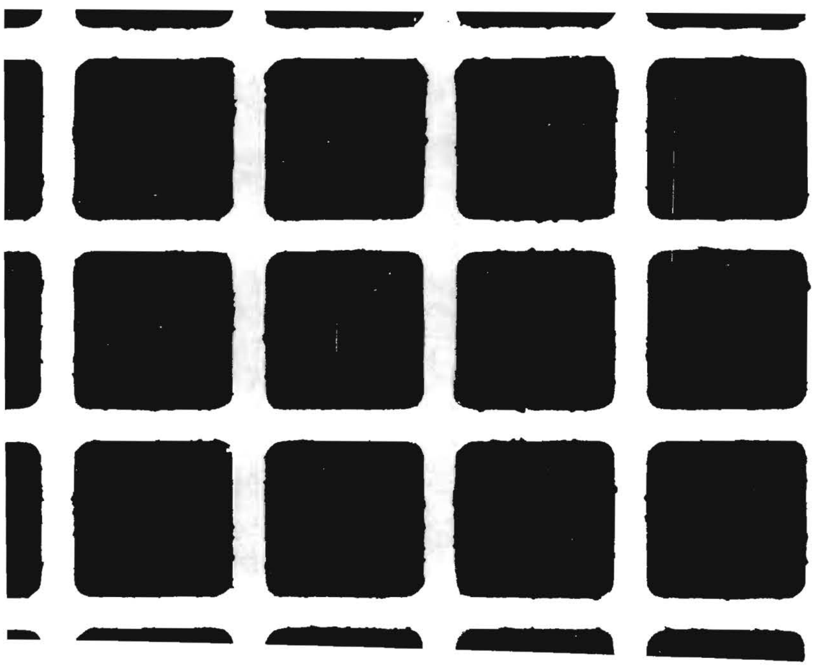

Fig. 4. 125 μm periodicity inductive mesh, 1000Å thick metal

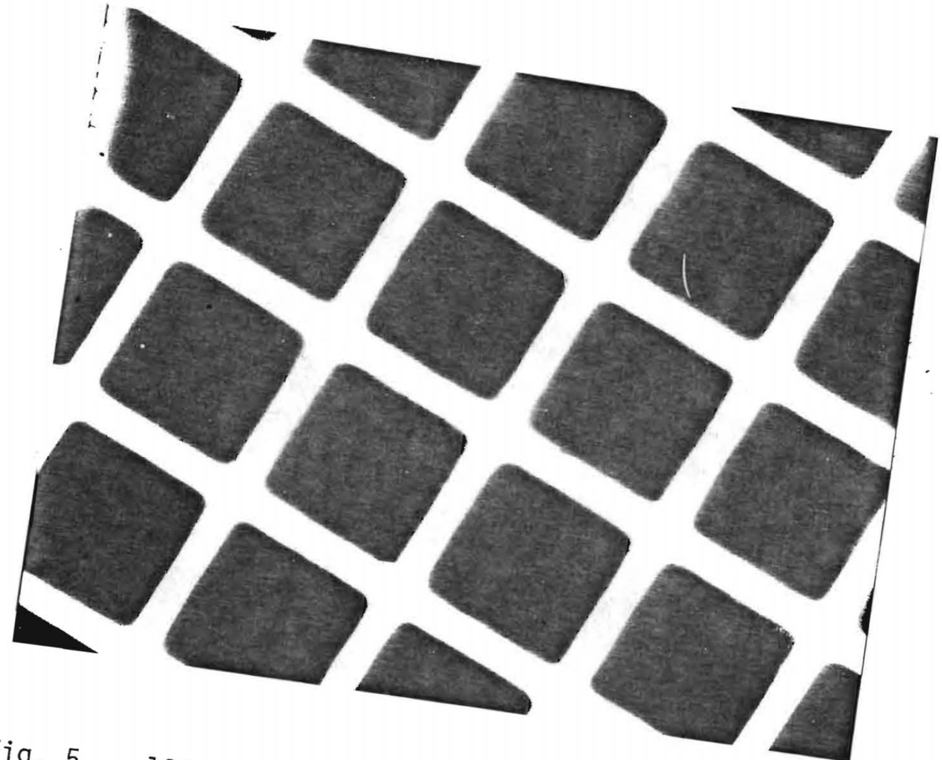

Fig. 5. 125 μm periodicity inductive mesh, 300Å thick metal

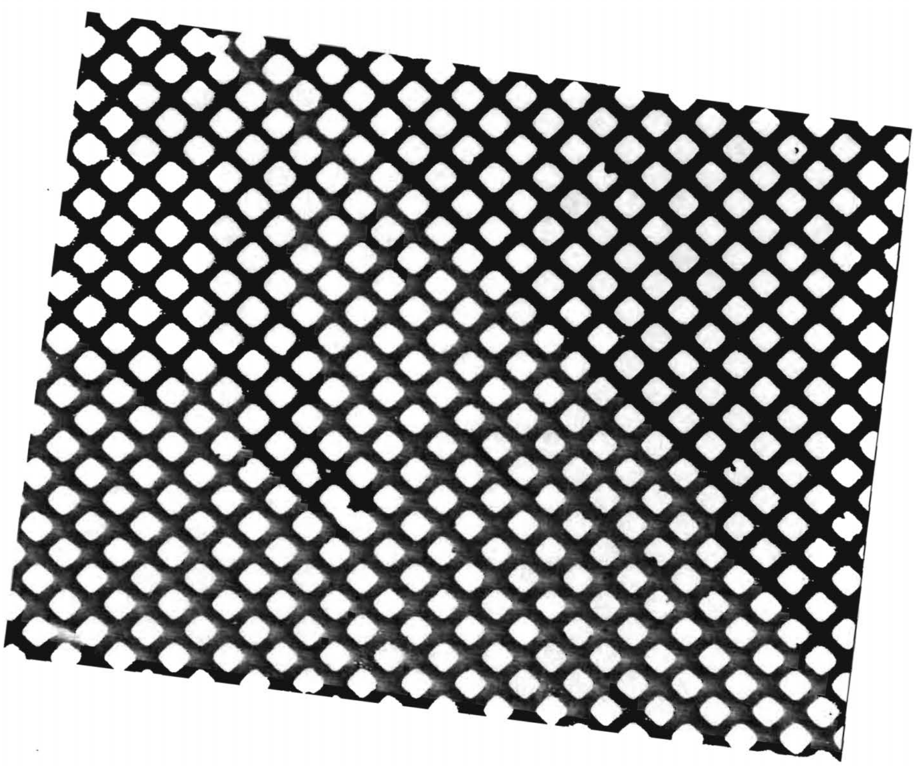

Fig. 6. 25 μm periodicity capacitative mesh

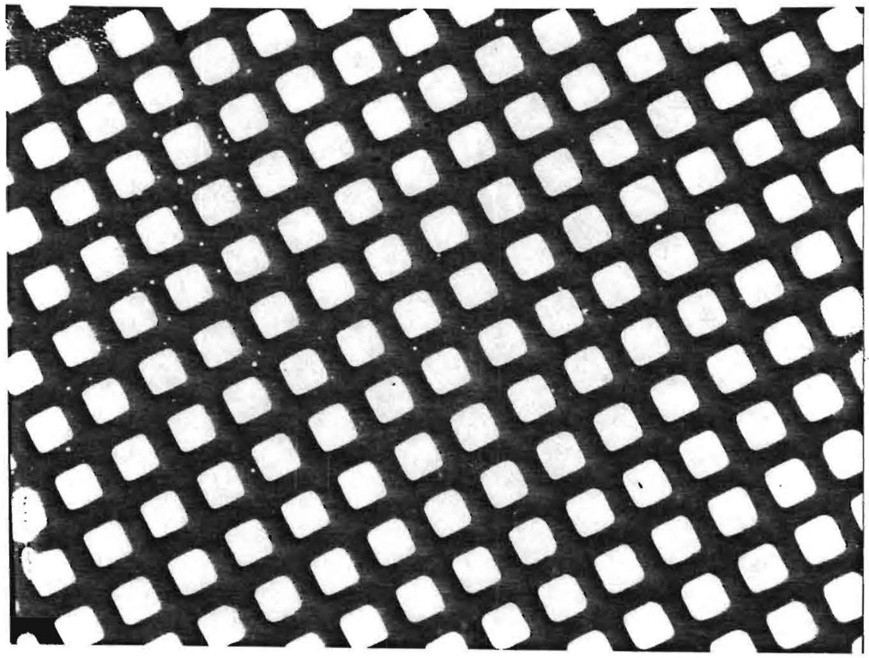

Fig. 7. 42 μm periodicity capacitative mesh

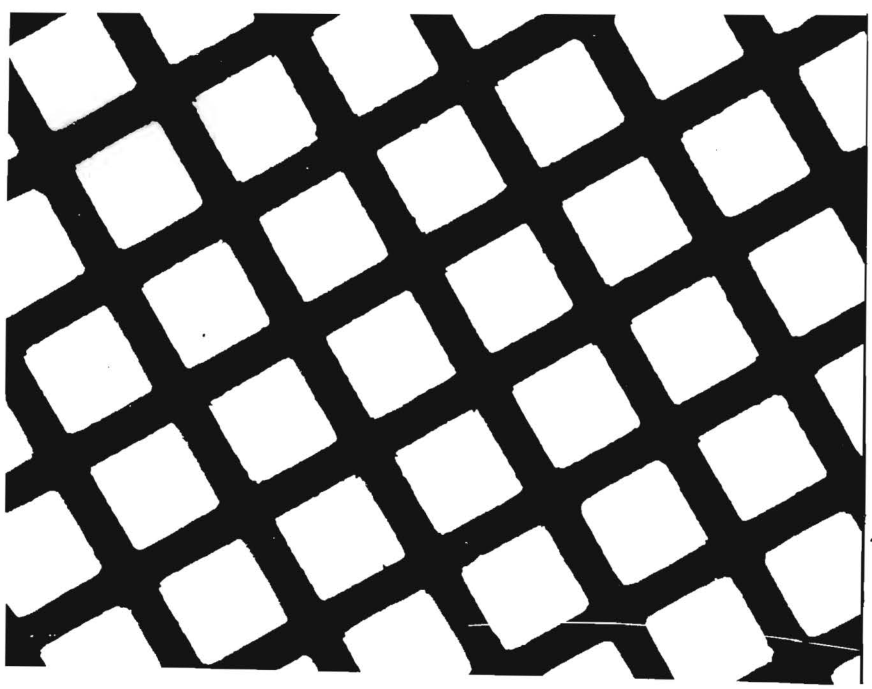

Fig. 8. 90 μm periodicity capacitative mesh

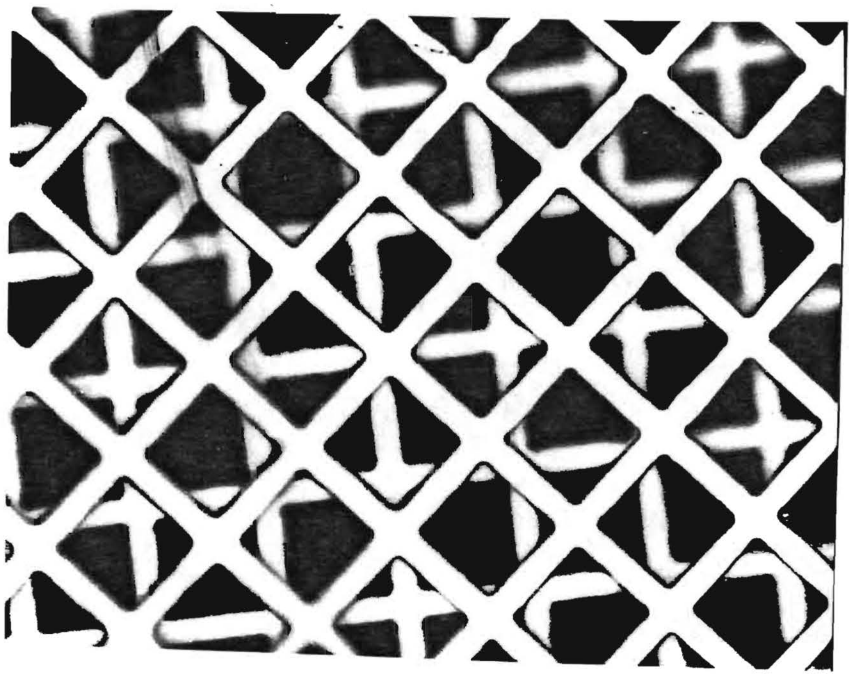

Fig. 9. Double-sided inductive mesh 100 μm periodicity on 50 μm thick quartz

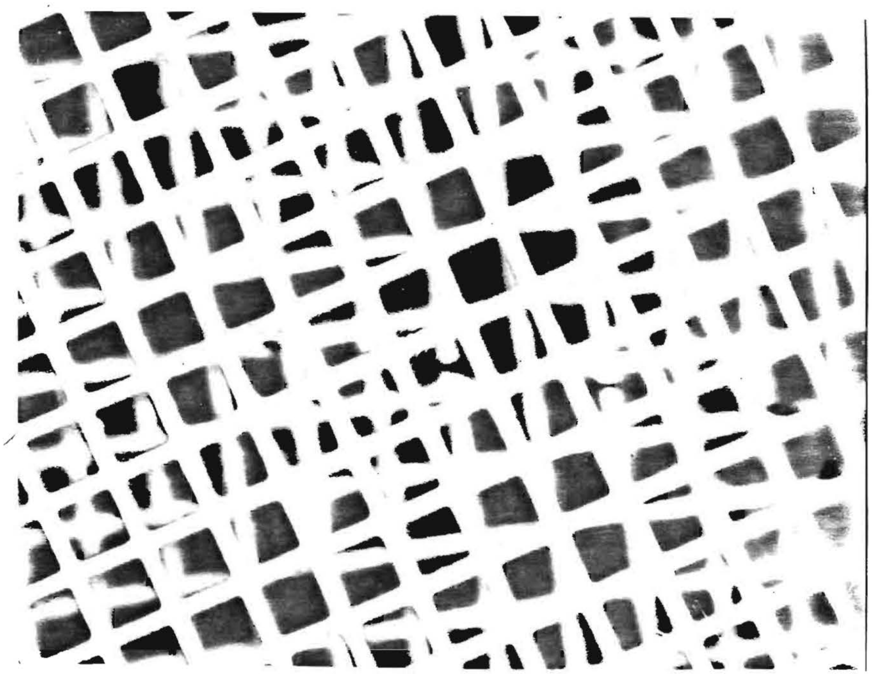

Fig. 10. Double-sided inductive mesh, 50 μm periodicity on 50 μm thick quartz

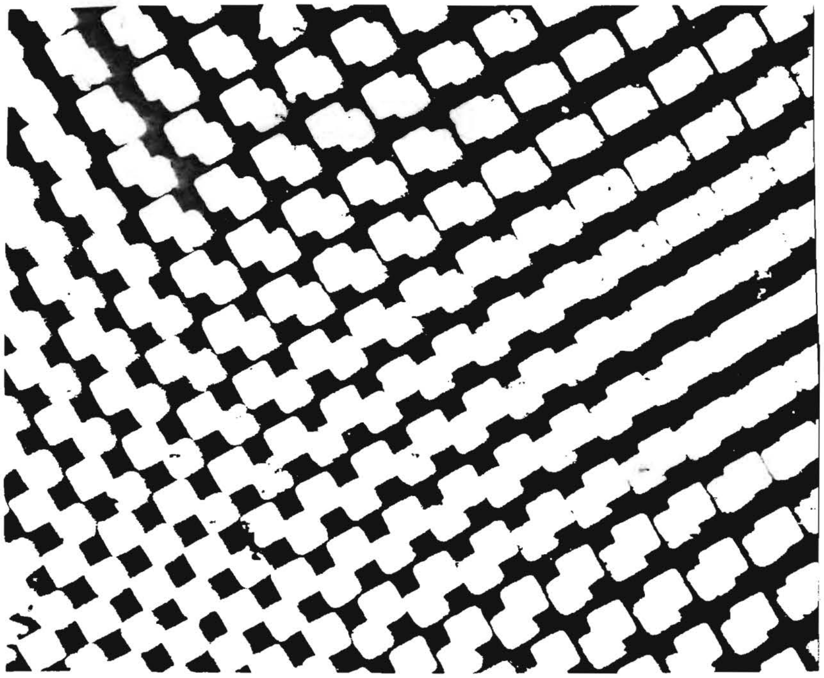

Fig. 11. Double-sided capacitative mesh, 42 μm periodicity

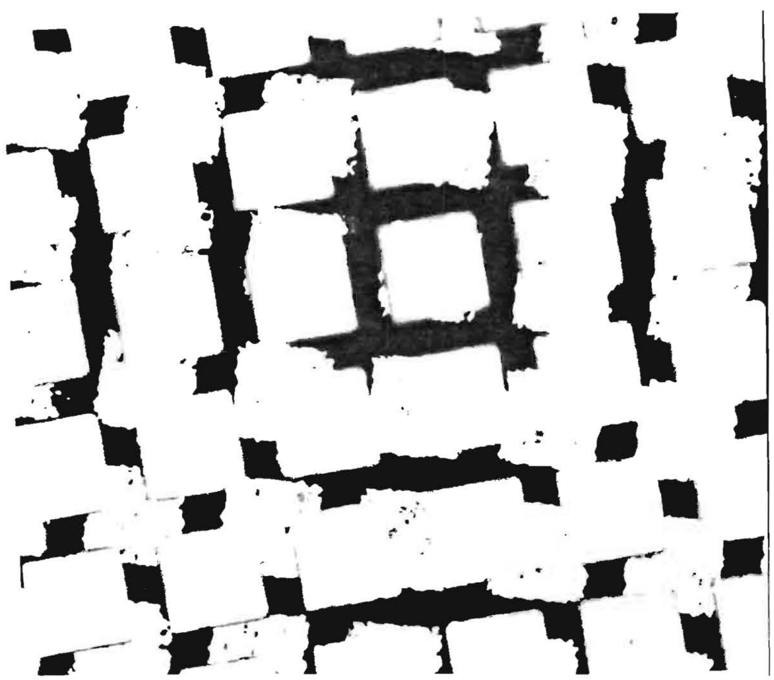

Fig. 12. Double-sided capacitative mesh, 90 μm periodicity

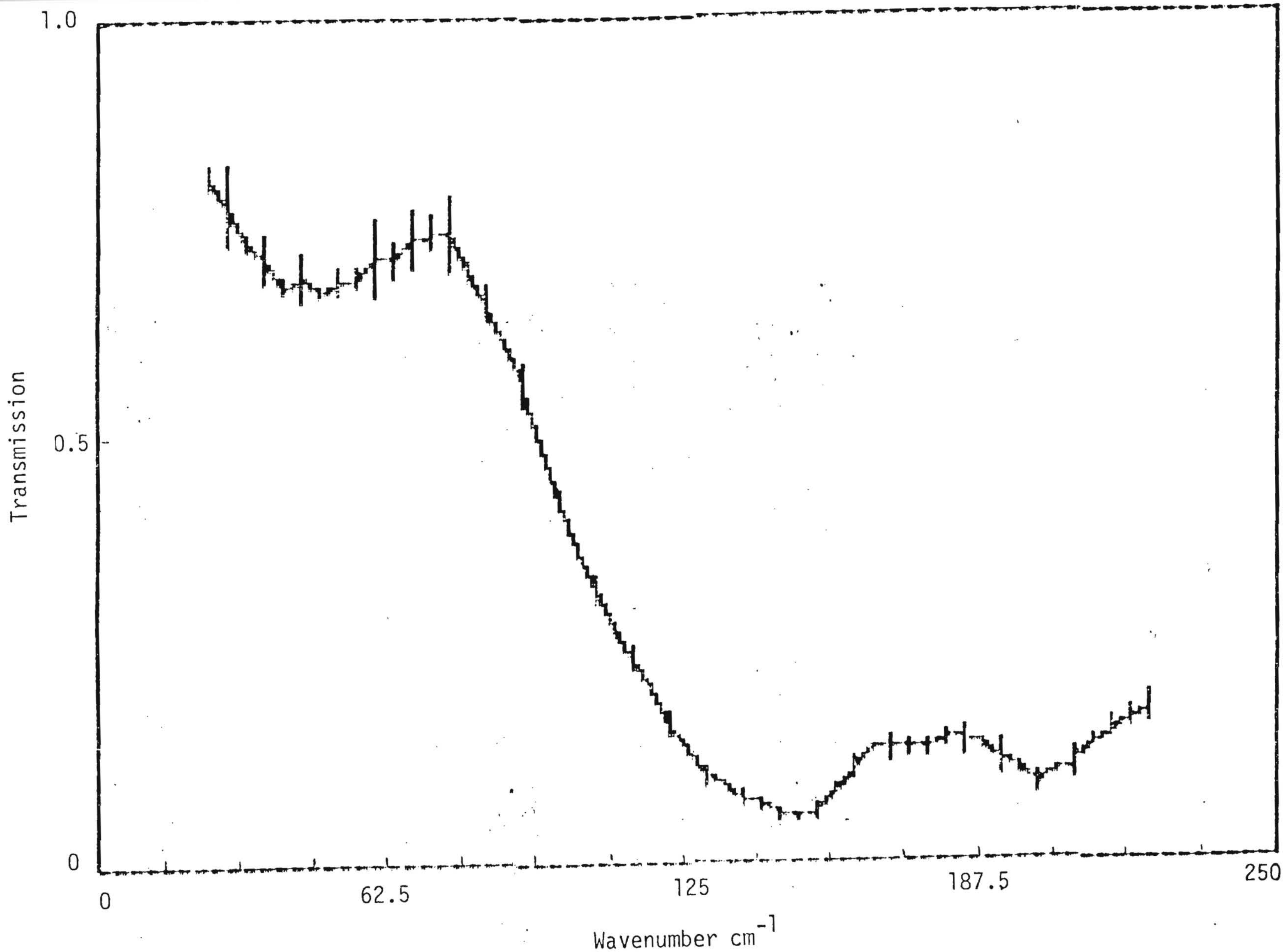

Fig. 13. Spectrum of double sided 42 μm capacitative mesh

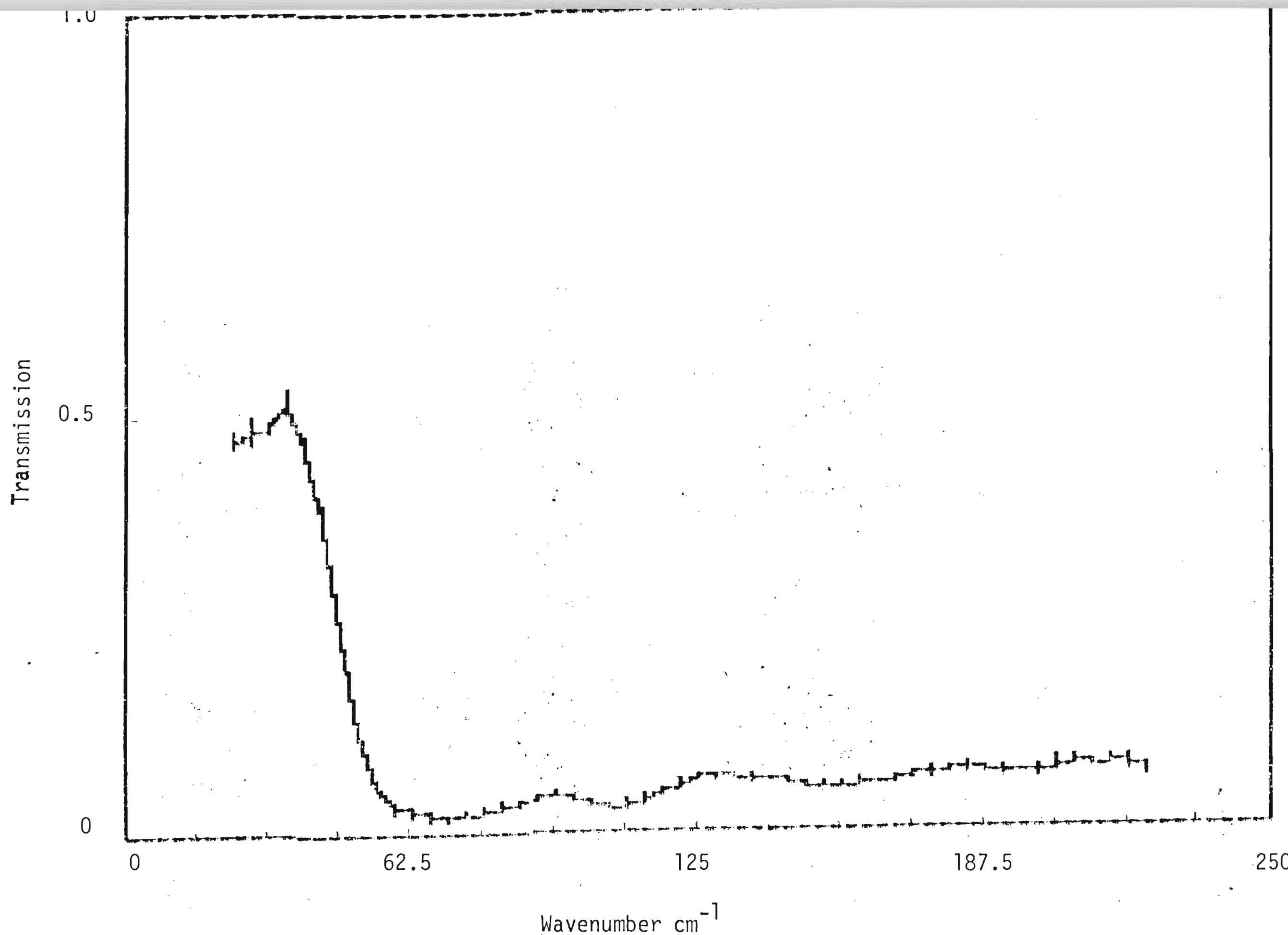

Fig. 14. Spectrum of double-sided 90 μm capacitative mesh

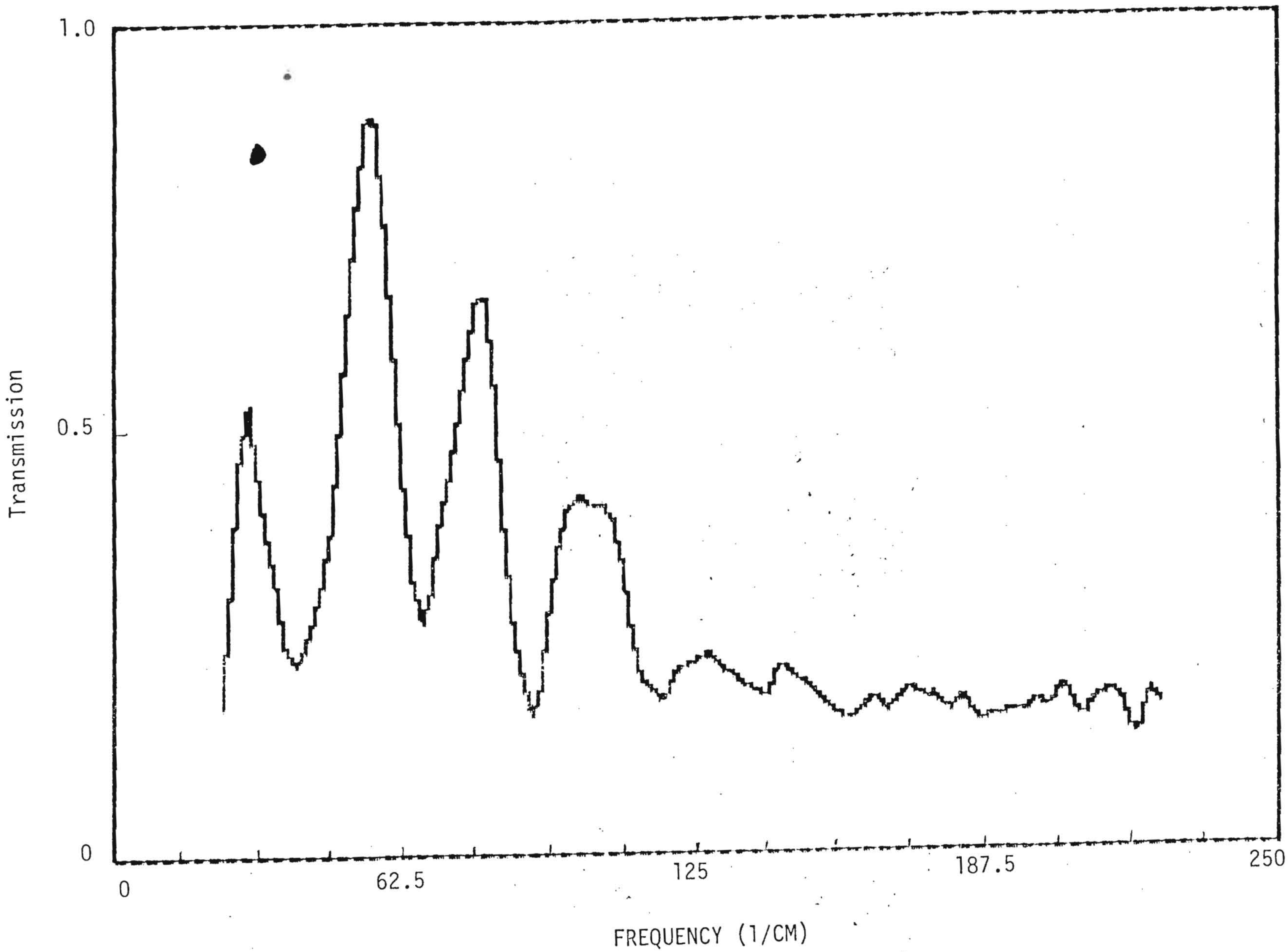

Fig. 15. Spectrum of double-sided 50 μm inductive mesh, quartz 50 μm thick