



# COM DEV LTD.



- MICROWAVE PRODUCTS
- CONSULTING SERVICES

IC

P  
91  
C654  
S79  
1984

P  
91

.C654

S79

1984

S-Class

DOC-CR-84-004

 COM DEV

COM DEV LTD.

MARCH, 1984

STUDY OF REFLECTIVE AND DOT

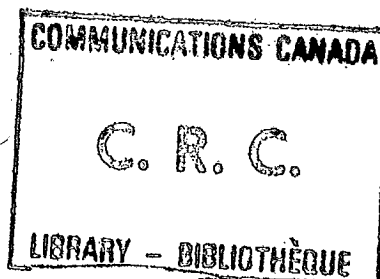
ARRAY COMPRESSORS (RAC's)

Reference No.: 06ST.36001-3-2326

Document Series # DOC-CR-SP-84-004

COM DEV PROJECT

No.: 2140



## EXECUTIVE SUMMARY

Surface Acoustic Wave (SAW) devices are passive microwave circuits fabricated on a piezoelectric substrate using integrated circuit technology. The small size, light weight and reliability of SAW components make them attractive for military and commercial applications. Today, SAW's are increasingly being used for radar and communications in terrestrial and satellite stations.

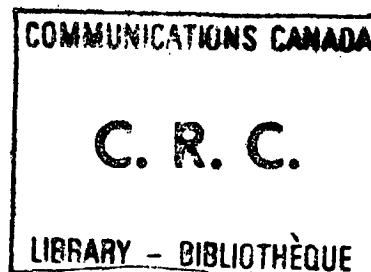
Prior to this contract COM DEV LTD. was established, under an NRC contract, as a Canadian source of SAW devices. The technology implemented was that of the traditional Interdigital Transducer (IDT) SAW structure. This present contract was awarded to COM DEV to carry out a technical study on the design and fabrication of a more advanced SAW structure, the Reflective Array Compressor (RAC). Three types of RAC's were investigated, namely:

- (1) Grooved Reflective Array Compressors (GRAC's)
- (2) Metallic Reflective Array Compressors (MRAC's)
- and (3) Dotted Reflective Array Compressors (DRAC's)

The above three technologies are presently being developed in the USA and Europe for high performance radar and communications systems.

As part of this contract a comparative analysis of GRAC's, MRAC's DRAC's and the traditional IDT structure was carried out in the areas of:

- design complexity
- fabrication complexity
- window function implementation
- defect tolerance
- maximum bandwidth and pulse length
- susceptibility to distorting effects
- phase compensation
- and -minimum required line width





To determine the accuracy of the design software, two sets of GRAC's, MRAC's and DRAC's were fabricated and tested. The measured results showed the GRAC devices to be superior in terms of electrical performance, followed by the DRAC and MRAC devices. In terms of fabrication costs the MRAC devices were the least costly followed by the DRAC and GRAC devices. Based on the cost performance of each device a table (Figure 26) was derived to detail the best option for a required level of performance.

Recommendations call for further study of the DRAC device in order to improve its performance to a level comparable to the more costly GRAC. Presently the GRAC electrical performance is only 12% better than that of the DRAC; but the GRAC cost is 160% higher in quantities of 10-100.



TABLE OF CONTENTS

	<u>PAGE</u>
EXECUTIVE SUMMARY	2
1.0 INTRODUCTION	5
2.0 REFLECTIVE ARRAY COMPRESSORS (RAC's)	7
2.1 Physics of Surface Wave Reflections	7
2.2 Weak Reflection Model	7
2.3 Frequency Response of a GRAC Device	9
2.4 Phase Compensation	12
2.5 GRAC Performance	12
3.0 METALLIC RAC's (MRAC's)	13
4.0 DOT ARRAY DEVICES (DRAC's)	15
5.0 SOME SOURCES OF ERRORS	16
6.0 THERMAL STABILITY	17
7.0 COM DEV REFLECTIVE ARRAY DEVICES	18
7.1 GRAC Devices	18
7.2 MRAC Devices	22
7.3 DRAC Devices	22
8.0 FABRICATION	24
9.0 COST AND PERFORMANCE ANALYSIS	27
10.0 CONCLUSIONS AND RECOMMENDATIONS	34

## 1.0 INTRODUCTION

Surface acoustic waves are successfully employed in a number of signal processing devices; such as delay lines, bandpass filters, phase coded matched filters, pulse compressors, spectrum analyzers, etc. In most cases the generation and detection of the surface acoustic waves, as well as the desired signal processing are performed by an array of electrodes (interdigital transducers) deposited on a piezoelectric substrate. The techniques for obtaining a desired transfer function with interdigital transducers are well established and have allowed SAW engineers to design highly sophisticated signal processing devices very successfully. However, interdigital transducer structures give rise to undesirable effects, such as multiple reflections, acoustic regeneration, bulk wave generation, surface-bulk waves mode coupling, variation of effective surface wave velocity across the array etc.

The more stringent the specifications the more these effects degrade the performance of a SAW device. One classical example is a dispersive delay line. For time bandwidth product larger than 1000 the second order effects become so important that pulse compression systems with sidelobe reductions to better than 25-30 dB are almost impossible to realize. Very narrowband filters ( $\sim 0.1\%$ ) which require a large number of electrodes in the interdigital transducers do not show acceptable performance due to the severe distortions caused by some of the effects mentioned above.

Alternate means of producing desired signal processing capabilities with surface acoustic waves have been investigated during recent years in order to produce devices relatively free of spurious effects.

Devices in which the signal processing is mostly performed by reflection gratings rather than interdigital transducers are generally called Reflective Array Compressors (RAC's). The name is derived from one of the most important applications, the pulse compression technique.

In RAC devices the interdigital transducers (IDT's) are used only to generate and detect the surface acoustic waves, whereas the signal processing is implemented by choosing an appropriate grating geometry. Figure 1 shows some of the different structures that have been in use. The input transducer generates and launches a wave that is reflected by the grating (s) towards the output transducer which converts the mechanical energy back to electrical energy via the piezoelectric effect.

The grating may consist of etched grooves, metallic strips or even metallic dots. In this report we shall call these devices GRAC's, MRAC's and DRAC's respectively. The word RAC will be used for any type of reflective array devices.

In 1968 Sittig and Coquin [1] noted that reflections of elastic waves from gratings in a strip or on a surface could be used to implement pulse compression and other types of signal processing functions. However, initial tests in strip-shear and surface wave configurations were unsatisfactory [1,2] and, with one exception, this line of development has been ignored. The exception is a device developed by T. Martin, known as IMCON [2]. The IMCON device uses the reflection of the lowest shear horizontal (SH) plate modes from symmetrical arrays of oblique grooves in the surface of a strip delay line to achieve large time-bandwidth pulse compression with low spurious signals. As the frequency of operation of the IMCON device is increased, the thickness of the strip must be reduced. Practical limitations on how thin a strip can be made lead to severe bandwidth restrictions. As a result, IMCON's are only practical for frequencies <30 MHz.



## 2.0 REFLECTIVE ARRAY COMPRESSORS (RAC's)

The surface acoustic wave reflective array device was developed by R. Williamson and co-workers at the Lincoln Laboratory, Massachusetts Institute of Technology during the early 70's. It consisted of two IDT's and one or two gratings, depending on whether a single or a double reflection is required. The gratings were made by etching grooves in the substrate. The groove depth can be kept to a constant value across the device or can be changed to suit a required weighting technique, as will be discussed later.

### 2.1 Physics of the Surface Wave Reflections

A complete description of surface wave scattering by a reflector has not yet been produced in closed form. This is mainly due to the fact that, unlike bulk wave reflections, surface wave reflection is a two dimensional problem. Despite the complexity of the problem, some simple and meaningful description of the process can be obtained for the conditions usually present in reflection grating devices, namely weak reflections. This implies that each line in the grating reflects a small amount of the SAW energy. It is the combined effect of many grooves that results in a relatively large overall reflection coefficient. When the weak reflection condition is not fulfilled severe degradation of the device performance is observed, unless corrections for multiple reflections are taken into consideration.

### 2.2 Weak Reflections Model

An AC voltage applied to an IDT generates many different elastic waves in a piezoelectric substrate. The surface acoustic waves (SAW's) differ from bulk acoustic waves (BAW's) because the SAW's satisfy a set of boundary conditions on the surface, BAW's are determined by the bulk properties of the substrate i.e. substrate

thickness. Figure 2 shows the two major techniques used for reflecting SAW's in a grating filter. Figure 2 (a) is a topographic perturbation and is the one encountered in GRAC devices. Figure 2 (b) shows the elastic substrate partially covered by a metallic overlay and is present in MRAC's and DRAC's devices.

In both cases an impedance mismatch is present although due to different mechanisms. In the case of Figure 2 (b) the conducting overlay couples to the surface wave through the piezoelectric effect and causes a reflection commonly referred to as a  $\Delta v/v$  reflection.

where  $v$  = free surface velocity  
and  $\Delta v$  = the velocity change due to the overlay

This coupling is always present regardless of how thin the overlay is and is strongly dependent on the piezoelectric coupling coefficient,  $k^2$ . This is the major drawback of MRAC devices as will be discussed later.

A heuristic argument leads to the conclusion that the reflection coefficient depends on the thickness of the overlay or the discontinuity height, normalized to the SAW wavelength in order to make it dimensionless ( $h/\lambda$ ). Expanding the reflection coefficient  $r$  in a Taylor's series we have

$$r = r_0 + Ch/\lambda + \text{higher order terms} \quad (1)$$

where  $h$  is the discontinuity height and/or overlay thickness. For the case of a conducting overlay  $r$  remains finite when  $h/\lambda$  goes to zero. For this situation  $r = r_0$ . For the case of a groove,  $r_0 = 0$  and the reflection coefficient is proportional to the frequency and the depth of the step, for small values of  $h/\lambda$ . This provides an excellent method for adjusting the reflectivity with frequency by varying the groove depth. This is indeed a very important feature in GRAC devices. Several authors have dealt with the problem of evaluating the constant  $C$  in equation (1) using different

approaches. It has been shown that good agreement between theory and experiment is obtained for small values of  $h/\lambda$  ( $<0.01$ ). For larger values of  $h/\lambda$  multiple reflections and therefore the higher order terms in equation (1) are important and a linear relationship between the reflection coefficient and the depth of a groove is no longer valid. Thus for large values of  $h/\lambda$  weighting cannot be easily accomplished without taking multiple reflection effects into account.

### 2.3 Frequency Response of a GRAC Device-Weak Coupling Model

Within the framework of the weak coupling model the transfer function of the U-path gratings is

$$H_o(\omega) = \sum_{m,n=1}^{2N} r_m r_n \gamma_{mn} e^{-j(\omega/v_z)(x_m + x_n)} \quad (2)$$

where  $N$  is the number of grooves in each of the two rows of the reflective array, and  $X_m$  is the distance from the first edge to the  $m^{\text{th}}$  edge in a row as measured along the centre line of the incident acoustic beam. Figure 2A shows the co-ordinate system used in the calculation. The reflection overlap factor  $\gamma_{mn}$  measures the fraction of the  $n^{\text{th}}$  edge in the second row illuminated by the  $m^{\text{th}}$  edge in the first row of reflectors

$$\gamma_{mn} = 1 - \frac{|X_m - X_n|}{d'} \quad \text{if} \quad |X_m - X_n| \leq d'$$

$$\gamma_{mn} = 0 \quad \text{if} \quad |X_m - X_n| > d'$$

where  $d'$  is the projection of a reflecting edge along the propagation direction. The  $\gamma_{mn}$  factor renders the double sum in (2) inseparable.  $r_m$  is the reflection coefficient at the  $m^{\text{th}}$  edge. The reflection coefficient of a groove,  $r_g$ , can be derived from the



reflection coefficient of a step. At oblique incidence,

$$r_g = 2jr \sin \frac{K W}{2 \cos \theta}$$

where  $r$  is the step reflection coefficient,  $W$  is the width of the groove as measured perpendicular to its length,  $K$  is the wavevector and  $\theta$  is the angle of incidence. If the grooves are enumerated by indices  $p$  and  $q$ , with  $X_p$  being the position of the centre of the  $p^{\text{th}}$  groove, (2) can now be written as

$$H_o(\omega) = \sum_{p,q=1}^N \left( \frac{C\omega}{\pi v_z} \right)^2 h_p h_q \sin \left( \frac{\omega W_p}{2v_z} \right) \sin \left( \frac{\omega W_q}{2v_z} \right) \gamma_{pq} e^{-j(\omega/v_z)(x_p + x_q)} \quad (3)$$

where  $h_p$  is the depth of the  $p^{\text{th}}$  groove and  $W_p$  is the width of the  $p^{\text{th}}$  groove measured along the propagation direction.

From (3) it is clear that there are three different ways of weighting a GRAC. Either the width ( $W_p$ ), the depth ( $h_p$ ) or the length ( $\gamma_{pq}$ ) can be varied in order to produce a required signal processing capability. Length weighting introduces phase distortions due to the difference of wave velocity in the free surface and under the groove. This effect is similar to the one observed in IDT devices when no dummy electrodes are used. Reflector width weighting has been applied to metallic RAC's with some success. However the most common technique for weighting a GRAC has been the depth weighting. One of the obvious advantages of this technique is that the same photomask can be used for devices with different weightings. For the case of a GRAC equation (3) becomes,

$$H_o(\omega) = \left( \frac{C\omega}{\pi v_z} \right)^2 \sin^2 \left( \frac{\omega W}{2v_z} \right) \sum_{p,q=1}^N h_p h_q \gamma_{pq} e^{-j(\omega/v_z)(x_p + x_q)} \quad (4)$$

where the groove width has been held constant. The factor in front of the summation imposes a slow amplitude variation on the response which tends to peak at a frequency slightly above  $\omega = \pi v_z / W$  or  $W = \lambda / 2$ .

Before we analyze equation (4) in more detail it is worth mentioning a practical advantage of  $90^\circ$  grating geometry over IDT and normal incidence structures (inline GRAC's, resonators, etc.) as far as the fabrication of high frequency devices is concerned. In order for the reflected SAW to reach the second grating with no phase distortion it is necessary that the centres of the grooves are separated by one wavelength along the propagation direction. Thus the period of the grating measured perpendicular to the grating lines is equal to  $\lambda \cos \theta$ . For  $90^\circ$  reflection this is approximately  $\sqrt{2}$  larger than the grating period required for normal incidence reflections and also  $\sqrt{2}$  larger than the electrode to electrode periodicity of an interdigital transducer operating at the same frequency. As a result, lower photomask resolution is required when fabricating oblique incidence gratings.

If the depth of the grooves is held constant in equation (4)  $H(\omega)$  will be proportional to the number of active grooves in each grating. The effective number of grooves is proportional to the instantaneous frequency. Therefore  $H(\omega)$  is proportional to the forth power of frequency for a linear chirped device. In order to compensate for this, the groove depth is made proportional to the square of the local groove periodicity.

Figure 3 shows the frequency response of the grating according to equation (4) when the groove depth is held constant. On Figure 4 similar results are shown for the case in which the groove depth is proportional to the square of the local periodicity. Both results are computer simulation of a device built according to the specifications listed in Table II. The fabrication of GRAC devices and the implementation of a non-uniform groove depth profile is dealt with later.

## 2.4 Phase Compensation

When SAW devices are used in a pulse compression system, deviation from ideal phase is a serious cause of distortion in sidelobe level performance, especially for large time bandwidth products.

The RAC geometry has a unique feature that allows these devices to be internally compensated to reduce any phase errors that might occur. In a chirp RAC different frequencies are predominantly reflected in small regions within the reflective arrays. Thus the SAW will cross the midline of the RAC at a specific position determined by a particular frequency. On piezoelectric substrates a metal film will slow the wave according to the  $\frac{\Delta v}{v}$  effect and thus advance the phase of a signal. Phase compensation is obtained by depositing a metal overlay between the grating and varying its width as a function of position along the midline to advance or delay the wave according to the phase errors obtained experimentally. The ability to phase compensate means that simplified design models can be employed for RAC devices and small phase errors, which result from second order effects not included in the models, can be eliminated by an empirically determined correction pattern.

## 2.5 GRAC Performance

Large Time Bandwidth (TB) products ( $> 10000$ ) have been achieved with GRAC devices. In a pulse compression experiment, sidelobes 35dB below the main lobe, using linear and non-linear waveforms, have been reported. Both long pulses (100  $\mu$ s) and large bandwidth (300 MHz) have also been achieved.

In short, RACs devices provide an excellent means for achieving large time bandwidth signal processors. The problem of bulk wave modes, velocity shifts, unwanted reflections, reradiation, propagation loss and dispersion common to interdigital devices are avoided at the expense of higher insertion loss and more complex fabrication steps. On a crystal of a given size, the GRAC geometry provides twice the dispersion of an inline device. Photolithographic and mask fabrication problems are also reduced.



### 3.0 METALLIC RAC's (MRAC's)

The MRAC device has the same geometry as the GRAC, except that the reflectors consist of strips of a conducting overlay, usually Aluminium.

One of the attractive features of a MRAC is that it can be fabricated in one lithographic step, therefore the fabrication cost is less when compared with a GRAC. There are, however, disadvantages to using a MRAC device. As mentioned in 2.1 the reflection of the acoustic wave is due to an impedance perturbation on the surface. For the case of a conducting overlay on a piezoelectric substrate the term  $r_0$  in equation (1) is not zero, regardless of the overlay thickness. This is due to the fact that the velocity of a SAW is reduced under a set of electrodes with respect to its value on a free surface, causing an electrical impedance mismatch. The reflection coefficient is also dependent on the overlay thickness due to the mass loading effect.

The mass loading effect can be controlled by varying the thickness of the overlay, but the electrical effect (hereinafter referred to as  $\Delta v/v$  effect) can only be controlled by using low coupling materials and therefore results in higher insertion loss. The alternative would be to model the multiple reflections caused by high coupling and take them into consideration at the design stage.

Three different approaches have been used to weight a metallic RAC. The most straightforward one is to change the length of individual reflectors according to the desired weighting [3]. Figure 5 shows this procedure. Also, since the reflection coefficient depends on the width of each individual reflector it is possible to achieve a desired weighting by varying the reflector width across the device. Finally, by shifting the positions of the metallic strips, amplitude weighting can be achieved in MRAC's. The reflected waves will be in phase when the wavelength at the incident wave is matched to the period of the reflective array. If the reflectors of a  $K^{\text{th}}$  group on one grating are shifted by an amount  $\Delta Z_K = \frac{\lambda_K}{2\pi} \Delta \Psi_K$  the reflected waves will interfere with a phase difference of  $2\Delta \Psi_K$ .

If the amplitude of the reflected wave of one reflector is  $a_0/2$  the resulting amplitude of the interfering waves will be  $a_k = a_0 \cos \Delta\psi_k$ . Therefore each desired amplitude weighting  $a_k/a_0$  can be achieved by shifting the positions of the reflectors of the  $k^{\text{th}}$  group by  $\Delta Z_k$

$$= \frac{\lambda_k}{2\pi} \arccos \frac{a_k}{a_0}$$

This latter technique has been successfully used to realize a non-linear doppler insensitive pulse compression system [4]. A clear presentation of multiple reflections effects is also given in Reference 4.

In short, MRAC devices provide an inexpensive alternative to GRAC's. However, the synthesis of a particular signal processing capability strongly depends on a good understanding of the multiple reflection effects. This is not usually the case on GRAC devices where high performance is obtained using relatively simple first order models.

#### 4.0 DOT ARRAY DEVICES (DRAC's)

As mentioned above the main disadvantage of MRAC's is the inherent high reflectivity of the  $\Delta v/v$  effect. One way of circumventing this problem, is to divide each reflector into small ( $\sim \lambda/4$ ) dots. Huang [5] has shown that if the dots are approximately  $\frac{1}{4} \lambda \times \frac{1}{4} \lambda$  in size, the electrical reflectivity goes to zero. The total reflectivity is thus due to mass loading, which can be controlled by the thickness of the overlay and the total number of dots in the array. A typical layout of a dot array device is shown on Figure 6.

L. Solie [6] was the first to introduce this idea. Various successful DRAC's have been reported recently. DRAC devices seem to have all the advantages of a MRAC over a GRAC (easy to fabricate, and inexpensive) and none of its disadvantages (severe multiple reflection effects, difficult to weight).

Weighting of a DRAC is, in principle, easy to achieve by making the overlay thickness and the number of dots in each row produce a reflectivity according to the desired waveform. Phase compensation can be implemented in the same manner as in a GRAC. One disadvantage of DRAC's over GRAC's is in the weighting process. In a GRAC device the same photomask can be used for different weightings since this is achieved in the groove depth pattern. For a DRAC device a different weighting requires a different photomask.



## 5.0 SOME SOURCES OF ERRORS

An additional advantage of GRAC's over its IDTs counterpart is that they are more defect tolerant. A broken or short electrode affects the performance of an IDT device severely, whereas the same type of defect (a void) in a groove will affect the reflectivity only locally.

Bulk wave interaction is usually a source of serious distortions on IDT devices. Although some bulk wave interaction (such as scattering and reactive storage) can take place in a grating, the effect on the performance of the GRAC is usually very small mainly due to the fact that the SAW reflection conditions are usually different from the bulk waves reflection conditions. In oblique incidence grating a scattered bulk wave travels at a significantly large angle relative to the direction of a reflected surface wave. Because surface wave transducers usually span a wide aperture (typically 100 wavelengths), they reject waves coming in at any angle except near normal incidence. Thus there exists a mode filtering action in oblique incidence grating that effectively rejects scattered bulk waves. If the surface waves are reflected twice, bulk waves are even further rejected. Generally, bulk waves are not a major source of GRAC performance degradation.

In pulse compression systems deviations from the ideal phase are usually a serious source of sidelobe level degradation. As discussed in Section 2.4, RAC devices can be phase corrected using a phase compensation plate between the gratings. With this technique RACs with phase errors of  $< 3^\circ$  have been reported.

## 6.0 THERMAL STABILITY

As with any other SAW device RACs are temperature sensitive. The vast majority of GRAC devices currently in use have been fabricated on  $\text{YZ-LiNbO}_3$  due to its strong piezoelectric coupling. However it is well known that  $\text{YZ-LiNbO}_3$  has a large temperature coefficient of delay in both the propagation direction and its perpendicular axis. As a consequence of this the relevant GRAC parameters are strongly temperature dependent. Therefore to obtain acceptable temperature performance with  $\text{LiNbO}_3$ , either a temperature controlled oven or an electronic compensation circuit is required. On the other hand this temperature dependence can be used advantageously to compensate for the differences among devices introduced by slight variations in the fabrication process. A temperature-stable GRAC requires zero temperature coefficient of delay (TCD) in two perpendicular directions, and thus the achievement of temperature stability is considerably more difficult for a GRAC than for an in line device where the well known ST cut of Quartz provides zero TCD for surface waves propagating parallel to the X axis.

Recently a new cut of Quartz which has two orthogonal directions of SAW propagation with zero TCD has been reported. However, since the material is quartz, the low value of the piezoelectric coupling constant limits the usable fractional bandwidth to approximately 6%, when conventional IDTs are used. We have made enquiries as to the availability of this material and been told that the maximum crystal size would be 4 inches. Longer crystals would have to be especially grown and ordered six months in advance.

## 7.0 COM DEV REFLECTIVE ARRAY DEVICES

Two sets of Reflective Array Devices were designed and built during the course of the present contract. The objective of this exercise has been:

A) Develop the necessary software and hardware to design, build and test reflective array devices.

B) Compare the performance of GRAC, MRAC, and DRAC devices built to identical specifications.

The specifications for the two sets are given in Table I and II. These specifications were chosen so that most of the fabrication could be done in-house. The GRAC devices were sent to Ion Optics Inc for ion milling. All masks were fabricated using COM DEV facilities. A computer program was also developed to convert the mask data into a format which could be read into a pattern generator if required.

### 7.1 GRAC Devices

Two GRAC devices with the specifications listed in Table I were sent to Ion Optics Inc. during the first week of January 1984 and returned on February 10th. After ion milling it was discovered that the aluminium layer deposited on the substrate to mask the groove positions, had been etched away. It is believed that the Al layer ( $1000 \text{ \AA}$  thick) was not thick enough to allow  $1200 \text{ \AA}$  deep grooves to be ion milled without sputtering the layer itself. After the experiment was carried out, we were informed by Ion Optics Inc. that the etching rate of Aluminium is 2.5 higher than the etching rate of  $\text{LiNbO}_3$ . Therefore, a  $3000 \text{ \AA}$  thick layer of Al would have been needed in order to ion mill  $1200 \text{ \AA}$  of  $\text{LiNbO}_3$ .

TABLE 1

SPECIFICATIONS FOR FIRST SET OF COM DEV RAC's

	GRAC 1	MRAC 1	DRAC 1
CENTRE FREQUENCY $f_0$ (MHz)	30	30	30
BANDWIDTH BW (MHz)	5.55	5.55	5.55
PULSE LENGTH T ( $\mu$ s)	12	12	12
GRATING WIDTH W ( $\lambda_0$ )	80	80	80
GROOVE DEPTH H ( $\text{\AA}$ )	1200	-	-
ALUMINIUM THICKNESS ( $\text{\AA}$ )	-	2000	6600
DOT SIZE ( $\lambda_0$ )			$\frac{1}{4} \times \frac{1}{2}$
NUMBER OF FINGER PAIRS IN IDT's	4	4	4

$\lambda_0$ : Wavelength at Centre Frequency  $f_0$

TABLE 2

SPECIFICATIONS FOR SECOND SET OF COM DEV RAC's

	GRAC 2	MRAC 2	DRAC 2
CENTRE FREQUENCY $f_0$ (MHz)	60	60	60
BANDWIDTH BW (MHz)	6	6	6
PULSE LENGTH T ( $\mu$ s)	10	10	10
GRATING WIDTH W ( $\lambda_0$ )	160	160	160
GROOVE DEPTH H ( $\text{\AA}$ )	2500	-	-
ALUMINIUM THICKNESS ( $\text{\AA}$ )	-	2000	7000 & 12000
DOT SIZE ( $\lambda_0$ )			$\frac{1}{4} \times \frac{1}{4}$
NUMBER OF FINGER PAIRS IN IDT's	6	6	6

$\lambda_0$ : Wavelength at Centre Frequency  $f_0$

The measurements made on the device indicate that the groove depth ( $1200 \text{ \AA}$ ) was insufficient to produce a significant reflection of the acoustic wave. The four finger pair transducers, designed to produce a relatively flat response over the 18.5% fractional bandwidth of this device, contributed a loss of  $\sim 23 \text{ dB}$ . A very weak response ( $\sim 75 \text{ dB}$ ) was observed at the frequencies of interest.

The groove depth is usually designed to be 0.1 - 0.5% of the wavelength in order to keep multiple reflections to a minimum. However, in this case the number of reflectors (181 in each grating) was not large enough to produce a significant reflection of the surface wave. A new GRAC was then designed with the specifications listed in Table II. Increasing the centre frequency to 60 MHz has the effect of increasing the number of grooves from 181 to 301 in each grating. Reducing the bandwidth to 6 MHz (10% fractional bandwidth) allows us to use six finger pair transducers with an expected loss of 7 dB per transducer.

The impulse response of the GRAC2 device is shown in Figure 7. Figures 8 and 9 show the frequency response of the untuned device over two different frequency sweeps. The insertion loss can be reduced by cancelling the interelectrode capacitance via an inductor connected in series with the transducer. Figures 10 and 11 show the frequency response for the device tuned in this manner. The insertion loss for the tuned device was reduced by 3.5 dB.

The amplitude slope in the passband is expected in an unweighted device, since the groove depth has been kept constant to  $2500 \text{ \AA}$ .

Both impulse and frequency response are very smooth and no signs of second order effects are present. The overall results for the GRAC device were the best obtained from the three different RAC's.

## 7.2 MRAC Devices

The first set of MRAC devices (called MRAC1) was designed with the specifications given in Table I. Two devices were built. Their impulse and frequency response are shown in Figure 12 - 15. The untuned devices showed an insertion loss of  $\sim 50$  dB, of which 23dB are due to the four finger pair transducers, leaving a total loss of 27dB in the gratings. Since the reflection mechanism is based on the shorting of the electric field ( $\Delta v/v$  effect), rather than on mass loading, a relatively thin Al layer was used ( $2000 \text{ \AA}$ ).

A second MRAC (called MRAC2) device was designed following the specifications of Table II. The impulse and frequency response are shown in Figures 16 and 17 respectively. This device is 10dB less lossy than MRAC1. However, the pulse is severely distorted. Second order effects (multiple reflections), which were not present on MRAC1, are clearly playing an important role in the response of MRAC2. This problem was anticipated and has been discussed in the previous paragraphs. These results verify our prediction that it would be difficult to design a high performance metallic array device without a good understanding and modelling of all the multiple reflections present.

## 7.3 DRAC Devices

Our first Reflective Dot Array Device (called DRAC1) was designed according to the specifications given in Table I. In order to avoid timely peeling of individual dots at the first stage of the artwork, two Rubylith masks were designed. One of them was a standard GRAC mask, while the second was a reticle with  $\lambda/4$  wide lines separated by  $\lambda/4$ . When these two masks were superimposed, dots of parallelogram shape were produced with a height of  $\lambda/4$  and a width of  $\lambda/2$ . Figure 18 is a microphotograph of a portion of this mask. Since the reflection mechanism on the DRAC device is mainly due to mass loading, a  $8000 \text{ \AA}$  layer of Aluminium was deposited on



the substrate. Electrical testing of this device showed a very weak signal ( $\sim 75$  dB) almost hidden in the electromagnetic feedthrough. The experiments indicate that not enough reflectivity was achieved with the 8000 Å thick dots.

The number of dots in a DRAC device is dependent upon the number of rows, the size of each dot and the separation between them. For a given centre frequency and time duration the number of rows is fixed. The size of the dots is also fixed since it has to be of the order of  $\lambda/4$ . It must also be noted that the shape of the dot is important since it determines the reflectivity ratio due to the  $\Delta v/v$  and mass loading effects.

Using the same fabrication technique outlined above, a new Dot Array Device (DRAC2) was designed. The specifications are given in Table II. The dot size was reduced to  $\frac{\lambda}{4} \times \frac{\lambda}{4}$  in order to avoid

electrical shorting effects. For this dot size, most of the reflection is due to mass loading.

A higher frequency (60 MHz instead of 30 MHz) and the same grating aperture allowed us to have 320 dots per row (160 on DRAC1). The transducers are also less lossy than those used in DRAC1. Two DRAC devices were fabricated, one with a 12000 Å thick Al layer, the other with a 7000 Å thick Al layer. Figures 19 and 20 show the impulse and frequency response of the 12000 Å device, respectively. Both results are quite satisfactory. The expanded pulse is fairly smooth and the frequency response has the typical shape of the Fresnel integrals for a linear chirp. Although the device is not weighted, no appreciable amplitude slope is observed, probably because of the small fractional bandwidth of the device. Finally, the impulse and frequency response of the 7000 Å DRAC2 device are shown on Figures 21 and 22 respectively.

## 8.0 FABRICATION

This section outlines the fabrication techniques for MRAC's, DRAC's and GRAC's. The special processing and equipment needed is also defined.

### 8.1 MRAC Fabrication

MRAC's are SAW devices with reflective arrays made from metallic strips. MRAC's are fabricated using the same equipment and steps involved in making IDT chirp devices. The process involves:

- Cleaning of SAW substrate (YZ-Lithium Niobate, Quartz)
- Coating of substrate with a thin layer (1000-6000 Å) of Aluminium
- Coating of the metallized substrate with positive photoresist
- Exposing the photosensitized substrate to UV light passing through the final glass mask, which contains a positive image of the device
- Developing the exposed area of the substrate
- Chemically etching the metal on the exposed areas of the substrate
- Stripping away any remaining photoresist
- Mounting and bonding of the device to a package

These steps are diagrammatically illustrated in Figure 23.

The two major differences in the fabrication of MRAC's and IDT's, with the same time bandwidth product, are:

- the length of substrate needed for the MRAC is less than that for the IDT
- and - metal thickness for the MRAC is greater than for the IDT.

## 8.2 DRAC Fabrication

DRAC devices are similar to MRAC's except that metallic dots, rather than metallic strips, make up the reflectors. Thus, the fabrication steps are exactly the same as those outlined in Section 8.1.

For un-weighted DRAC devices with small time dispersions ( $<20\mu\text{s}$ ), the mask can be made using two pieces of rubylith. One piece of rubylith would contain horizontal lines and the other vertical lines. Superimposing these two pieces of rubylith produces the effect of rectangular dots. This technique, however, cannot be used for making masks of weighted DRAC devices, since the number of dots in each row varies and the position of each dot in a row is randomized.

Masks for weighted DRAC devices are made from a computer driven Pattern Generator (PG). The PG can then be programmed to vary the number and position of dots in each row. The cost of a PG produced mask is usually 5 - 10 times higher than the cost of a similar mask made by rubylith reduction techniques. However, it is worth noting that for the same TB product, the price of a DRAC mask can be 3 times greater than the price of a similar MRAC or GRAC mask.

## 8.3 GRAC Fabrication

Since GRAC devices contain grooves in the SAW substrate, the fabrication process is generally more complex than those outlined for MRAC's and DRAC's. GRAC fabrication required extra processing stages and specialized milling equipment.

GRAC devices were first made at MIT Lincoln Labs by H. Smith et al [7] using a modified Veeco ion-milling machine, Figure 24. The value of ion machining lies in its ability to remove small amounts of material in a deterministic manner. Other methods of micro-machining, such as lasers, electron beams and chemical etchants, are much less controllable and are used to cut completely through layers rather than to fabricate predetermined depths.

In the ion-milling machines, used for GRAC devices, ions are generated by an ion source (Kaufmann type) in a separate chamber, and accelerated into the main high vacuum chamber in which the substrate is located. The substrate is mounted on a water cooled stage, which is driven by an external stepping motor. To avoid chemical interactions, the rare gases are the obvious choice for the ion source. Argon is preferred, since there is little technical or economic advantage in using Krypton or Xenon.

In GRAC devices the pattern for the reflective array, input and output IDT's are first etched into the aluminium coating, following the same steps described for a MRAC device (Figure 23). The thickness of the aluminium coating must be greater than twice the maximum groove depth, since the aluminium overlay is also machined with the substrate. The input and output IDT's are covered with a protective layer of photoresist, and the substrate exposed to the ion-beam, Figure 25. The depth of etching is varied by controlling the length of time a groove stays under the ion-beam.

In addition to total ion exposure time, the depth of a groove depends on:

- the substrate material
- ion-beam energy
- ion-beam pressure
- and - ion-beam angle of incidence

On completion of ion-milling, the substrate is removed from the chamber, and the protective layers of aluminium and photoresist stripped. The GRAC device is then ready for mounting and bonding to its package.

## 9.0 COST AND PERFORMANCE ANALYSIS

This section outlines the cost of fabricating combined IDT structures, MRAC's, DRAC's and GRAC's. The electrical performance of these devices is also compared. Finally, based on an analysis of the cost performance trade-off, recommendations are made as to the most attractive options.

### 9.1 Cost Analysis

An analysis of the cost for fabricating combined IDT's, MRAC's, DRAC's and GRAC's is carried out assuming the devices are built to the specifications given in Table 3. These specifications are taken from the Fast Frequency Hopper defined in the Signal Processing contract.

TABLE 3: ELECTRICAL SPECIFICATIONS

Centre Frequency	=	250 MHz
Time Dispersion	=	104 $\mu$ s
Bandwidth	=	100 MHz
Waveform	=	Linear Chirp

#### 9.1.1 Substrates

The combined IDT structure will require 2 devices, each with 52 $\mu$ s time dispersion, cascaded together to produce 104 $\mu$ s. Therefore, the IDT combination would require two pieces of substrate, each 7.5 inches long. The MRAC, DRAC and GRAC devices would only need one 7.5 inch substrate.

#### 9.1.2 Mask Generation

The combined IDT's would require two masks, but each mask will be half the price of the mask for a MRAC, DRAC or GRAC. Therefore, the total price for the two masks needed by the IDT's would be the same as the single mask needed by the MRAC, DRAC or GRAC. The MRAC and GRAC masks will cost the same, and the DRAC mask will be about twice as costly, since the P.G. will use more flashes to generate the large number of dots.

#### 9.1.3 Circuit Transfer

Circuit transfer is carried out twice for the IDT structure, since there are two substrates.

#### 9.1.4 Ion-Milling

Ion-milling is only necessary for the GRAC device. It is estimated that 1 day would be required to ion-mill a GRAC 7.5 inches long.

#### 9.1.5 Packaging

The combined IDT structure would require two packages, each similar to the MRAC, DRAC or GRAC package, or one larger package to accommodate both substrates.

### 9.1.6 Cost Comparison

The estimated fabrication cost for each type of device is summarized in Table 4. From this table it can be seen that the cost of producing the MRAC device is the lowest, while the ion-milled GRAC is the most expensive. If the DRAC mask did not require the large number of flashes then the DRAC device would be as inexpensive as the MRAC device.

TABLE 4: ESTIMATED COST

PROCESS	COMBINED			
	IDT's	MRAC	DRAC	GRAC
1. Substrate	\$2,000	\$1,000	\$1,000	\$1,000
2. Mask	\$2,000	\$2,000	\$4,000	\$2,000
3. Circuit Transfer	\$ 200	\$ 100	\$ 100	\$ 100
4. Ion-Milling	-	-	-	\$3,000
5. Packaging	\$ 500	\$ 250	\$ 250	\$ 250
<b>TOTAL</b>	<b>\$4,700</b>	<b>\$3,350</b>	<b>\$5,350</b>	<b>\$6,350</b>

In Table 5 the estimated unit cost in quantities of 10 and 100 is presented.

The impact of the DRAC mask on the total cost has now disappeared making this device as competitive as the MRAC in terms of price. The GRAC is still the most expensive alternative, because every device has to be ion milled.

TABLE 5: ESTIMATED UNIT COST IN QUANTITIES OF 10 & 100

NUMBER OF UNITS	COMBINED IDT'S	MRAC	DRAC	GRAC
10	\$2900	\$1550	\$1750	\$4550
100	\$2720	\$1370	\$1390	\$4370

## 9.2 Performance Analysis

Based on the specifications given in Table 3, a prediction is made on the electrical performance of the combined IDT structure, MRAC, DRAC and GRAC.

### 9.2.1 Insertion Loss

For the two cascaded IDT structures, it is expected that each device would contain 20 dB insertion loss, resulting in a total of 40dB loss. The MRAC and DRAC devices should have relatively larger losses (45 - 50 dB) due to the acoustic losses in the metallic strips and dots. The GRAC device should have the least loss, since there are no metallic reflectors, and grooves are more efficient acoustic reflectors.

### 9.2.2 Amplitude Phase Ripple

Amplitude and phase ripple in SAW devices are primarily due to:

- Triple Transit Echo (TTE)
- Electromagnetic Feedthrough (EMF)
- Electric Field Shorting (EFS)
- Diffraction
- Finger Reflections

and - Bulk Modes

The combined IDT structure will suffer from all of these effects and thus exhibit the worst amplitude and phase ripple. The MRAC device performance will be severely distorted by the EFS effect. The ripples in the DRAC device will be mostly due to diffraction from the numerous tiny dots. The GRAC device will have the minimum amplitude and phase ripple, since grooved arrays are less subject to field shorting, finger reflections, diffraction and bulk modes. The MRAC, DRAC and GRAC devices have the added advantage that phase compensation can be easily implemented using metallic strips between the reflective gratings.



### 9.2.3 Compressed Pulse Side Lobe Level

Side lobe levels in a compressed pulse is directly related to the type of weighting function implemented, and the deviation in the phase and amplitude response. Therefore, the GRAC device should possess the lowest side lobe level, and the combined IDT structure the highest.

### 9.2.4 Performance Comparison

The predicted electrical performance for each type of device is summarized in Table 6. From this table it can be seen that the GRAC device is the structure with the best electrical performance. The combined IDT structure and the MRAC possess the worst overall performance. It is felt, however, if a design could be implemented to compensate or eliminate the EFS effects in the MRAC, this device could have as good a performance as the DRAC device.

TABLE 6: ELECTRICAL PERFORMANCE

MEASUREMENT	COMBINED			
	IDT's	MRAC	DRAC	GRAC
1. Insertion Loss(dB)	40	50	45	35
2. Amplitude Ripple(dB)	$\pm 1.0$	$\pm 0.8$	$\pm 0.6$	$\pm 0.4$
3. RMS Phase Error (degrees) **	$\pm 8$	$\pm 4^*$	$\pm 4^*$	$\pm 4^*$
4. Compressed Pulse Side Lobe(dB)	27	32	37	42

\* Phase Compensation Built In

\*\* RMS Phase Deviation from ideal Phase Response



### 9.3 Cost - Performance Trade-Off

Tables 4, 5 and 6 indicate that for a high performance device (side lobe level of compressed pulse  $>40\text{dB}$ ) the only alternative would be the GRAC structure. If the performance could be relaxed to  $>35\text{dB}$ , then the DRAC device would be the best cost-performance solution. If a lower level of performance could be tolerated the MRAC device becomes the best cost-performance option.

Contrary to our initial belief there appears to be no economic or technical advantage to using the combined IDT structure. The combined IDT structure should only be considered if the total time dispersion is below  $52\mu\text{s}$ , since only one substrate and mask would be needed. The resulting cost of the IDT structure would be \$2,700, making it the best cost option for devices below  $52\mu\text{s}$ .

Based on Tables 4, 5 and 6 a chart was drawn to display the best cost-performance options, Figure 26, for a given compressed pulse side lobe level and time dispersion. The most striking feature of this chart, is that it clearly illustrates that there is a large area for which the relatively inexpensive MRAC device could be used.

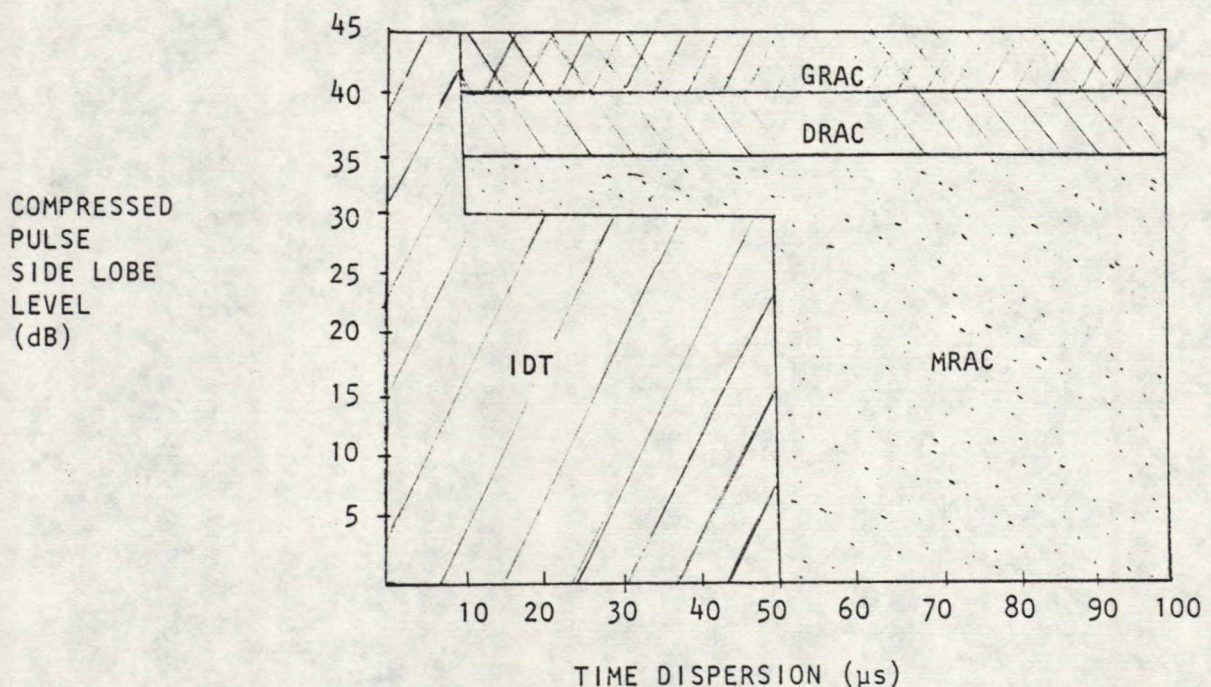


FIGURE 26: Recommended options for a given time dispersion and compressed pulse side lobe.



TABLE 7: COMPARISON BETWEEN IDT AND RAC DEVICES

		IDT	GRAC	MRAC	DRAC
1.	Wave front distortion due to Apodization.	Yes	No	No	No
2.	Multiple Reflections	Yes	No	Yes	No
3.	Acoustic Re-generation	Yes	No	Yes	No
3.	Bulk Wave Interaction	Yes	No	No	No
4.	Phase Compensation	No	Yes	Yes	Yes
5.	Windowing Implementation	Simple	Difficult for Complex Waveforms	Difficult for any Waveform	Simple
6.	Maximum Pulse Length on LiNbO <sub>3</sub> (μs)	~60	~120	~120	~120
7.	Maximum % Bandwidth	<100%	< 50%	< 50%	< 50%
8.	Design Complexity	High	Low	Very High	High
9.	Defect Tolerance	Bad	Good	Bad	Good
10.	Fabrication Complexity	Low	High	Low	Low
11.	Minimum Line Width	0.125λ	0.5λ	0.5λ	0.25λ

## 10.0 CONCLUSIONS AND RECOMMENDATIONS

The basic requirements for the design and synthesis of Reflective Array Devices have been established at COM DEV during this contract.

Reflective Array Devices have proved to be an excellent means of achieving high TB product SAW devices, enhancing the capabilities of many different signal processor subsystems, such as Pulse Compression Filters, Frequency Synthesizers, Fourier Transformers, etc.

The use of RAC devices minimizes distortions such as acoustic regeneration, bulk wave modes coupling, unwanted reflections, dispersion, etc. usually associated with interdigital structures. A summary of the properties of IDT and RAC devices is shown in Table 7.

Our results, supported by information found in the literature, indicate that better performance can be achieved with DRAC's and GRAC's than with MRAC's for the same level of design complexity. The purchase of an ion milling machine will enable COM DEV to fabricate high performance GRAC devices. For more modest TB product, high performance can be achieved with Dot Array Devices. Due to the ease of fabrication of DRAC's when compared with GRAC's and consequently the lower cost, it is recommended that R & D on DRAC devices should be pursued.

REFERENCES

- [1] E. K. Sittin and G. A. Coquin - "Filters and Dispersive Delay Lines Using Repetitivity Mismatched Ultrasonic Transmission Lines". IEEE Trans. Sonics. Ultrason., Vol SU-15, pp 111-119, Apr. 1968.
- [2] T. A. Martin - "The IMCON Pulse Compression Filter and its Applications", IEEE Trans. Microwave Theory Tech. Vol. MTT-21, No. 4, April 1973, pp. 186-194.
- [3] F. Marshall, E. Paige and A. Young, "Amplitude Weighting of SAW Reflecting Array Structures" 1974 Ultrasonics Symposium Proceedings, pp 202-204.
- [4] G. Riha, H. Stocker, R. Veith, W. Bulst, "RAC Filters with Position Weighted Metallic Strip Arrays", 1982 Ultrasonics Symposium Proceedings, pp 83-87.
- [5] F. Haung and E. Paige, "Reflection of Surface Acoustic Waves by Thin Metal Dots", 1982 Ultrasonics Symposium Proceedings, pp. 72-82.
- [6] L. Solie, "Surface Acoustic Wave Reflective Dot Arrays", Appl. Phys. Letters, Vol. 28, pp 420, 1976
- [7] H.I. Smith, R.C. Williamson and W.T. Brogan "Ion Beam Etching of Reflective Array Filters", IEEE Ultrasonics Symposium Proceedings, 1972, p. 198.



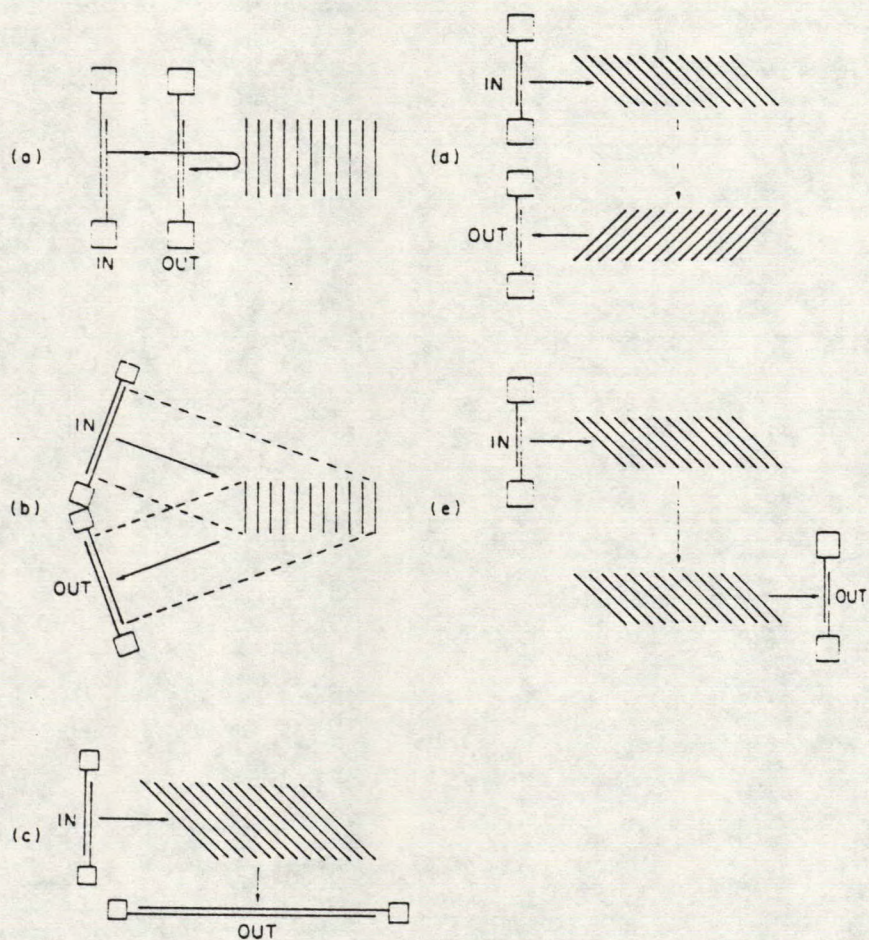


Fig. 1 Various structures for Reflective Array Devices



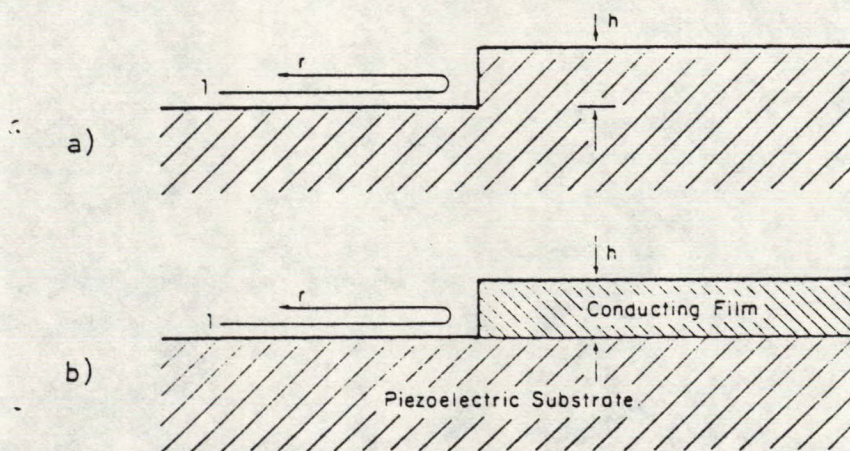


Fig. 2 Surface perturbations in a Reflective Array Device



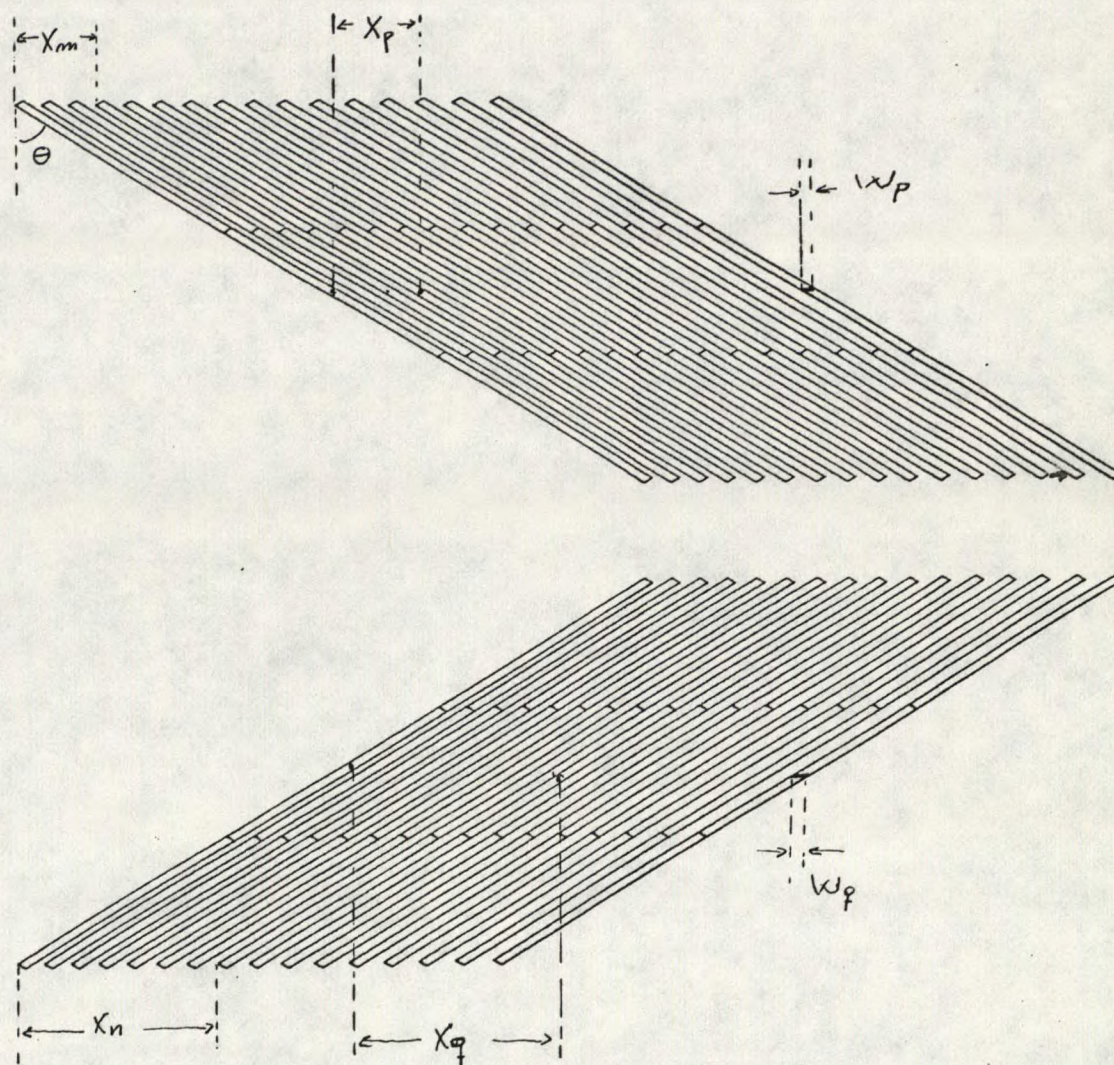
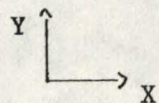
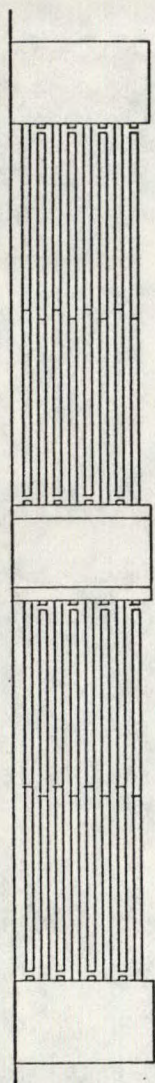


FIGURE 2A



NORMALIZED INSERTION LOSS

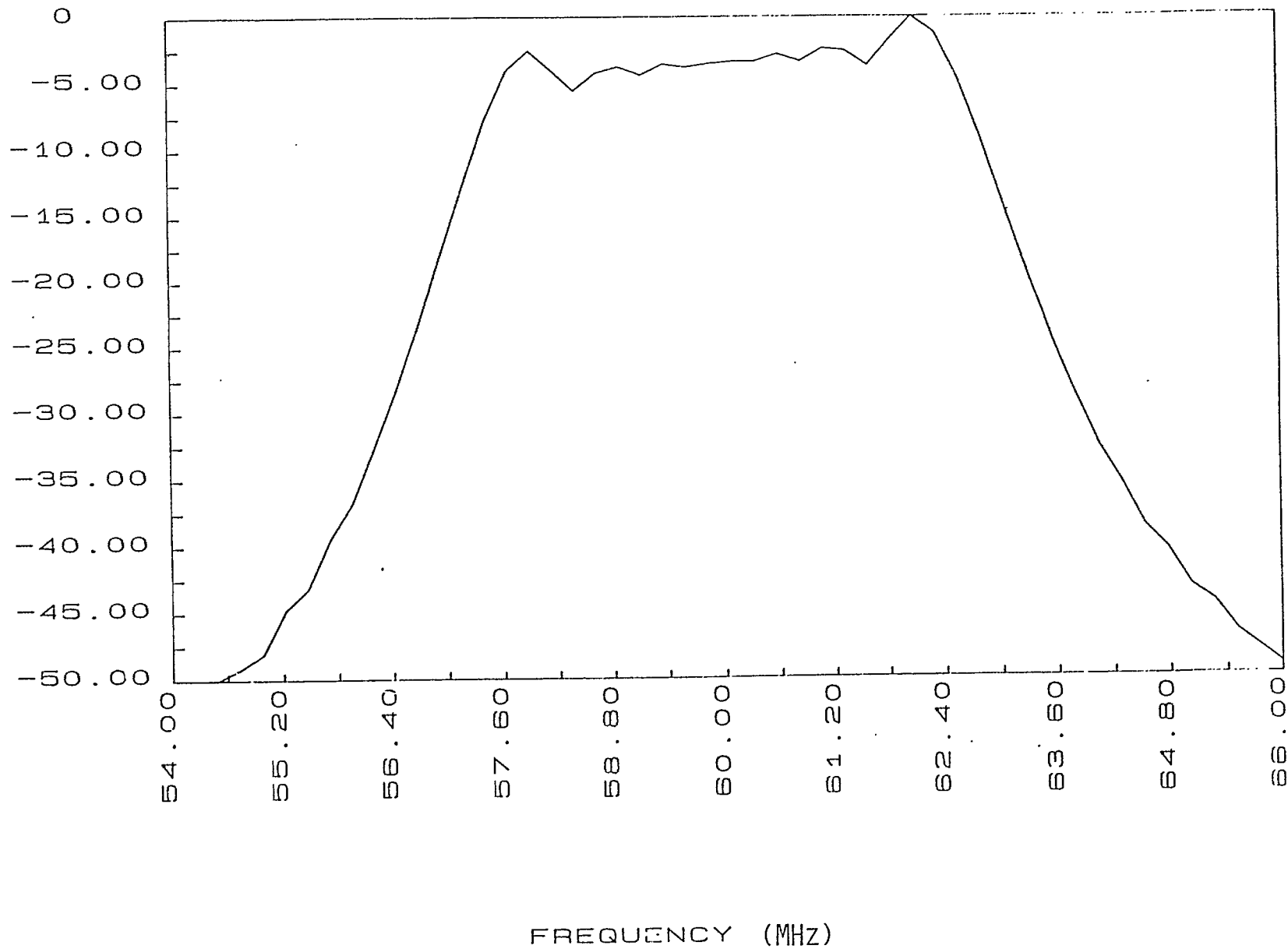


Fig. 3 Grating response for constant groove depth

NORMALIZED  
INSERTION LOSS

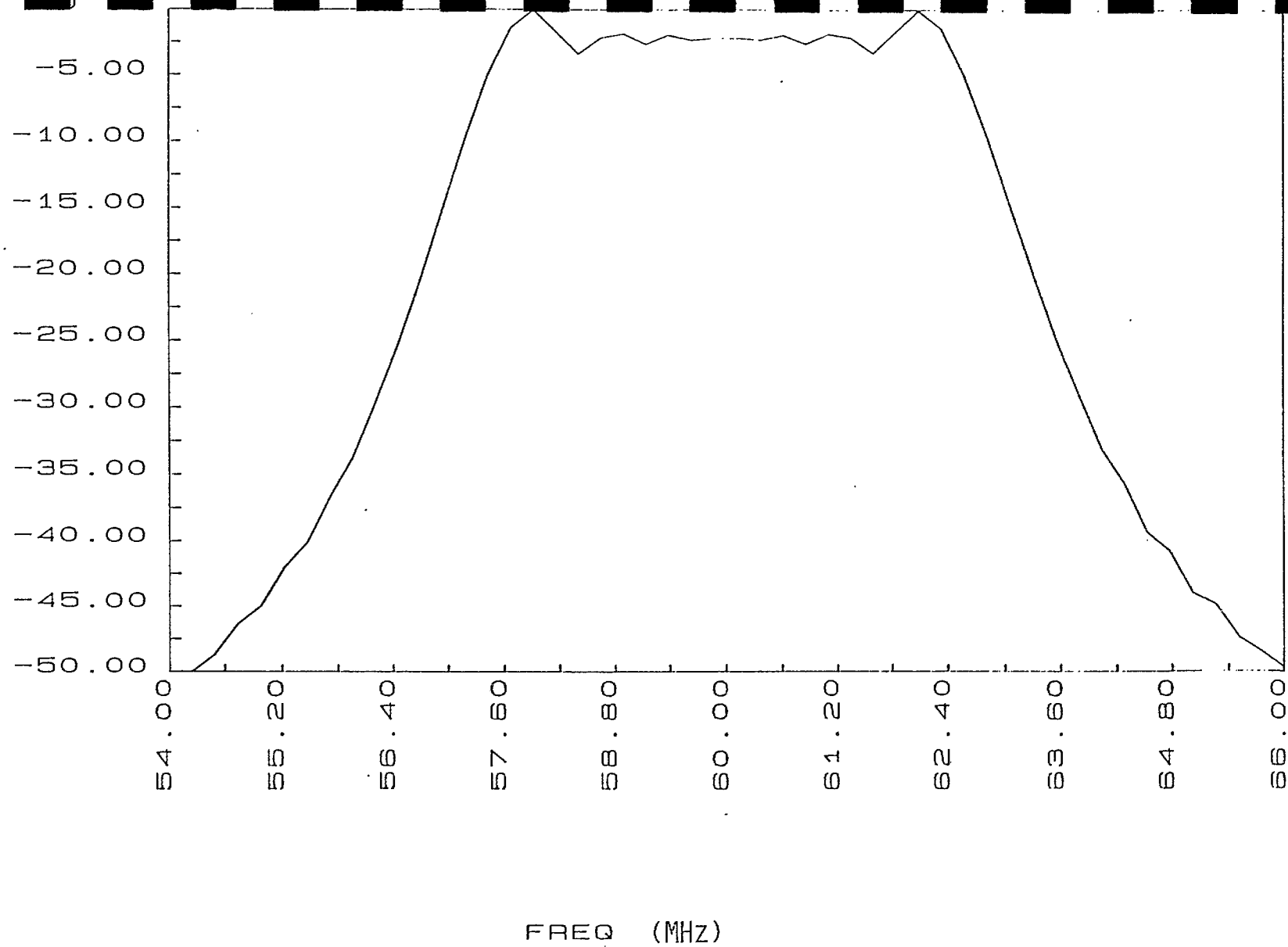


Fig. 4 Grating response - Groove depth proportional to square of local periodicity

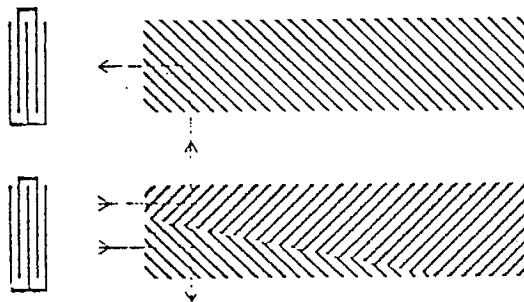


Fig. 5 Length weighting in a Metallic Reflective Array Device

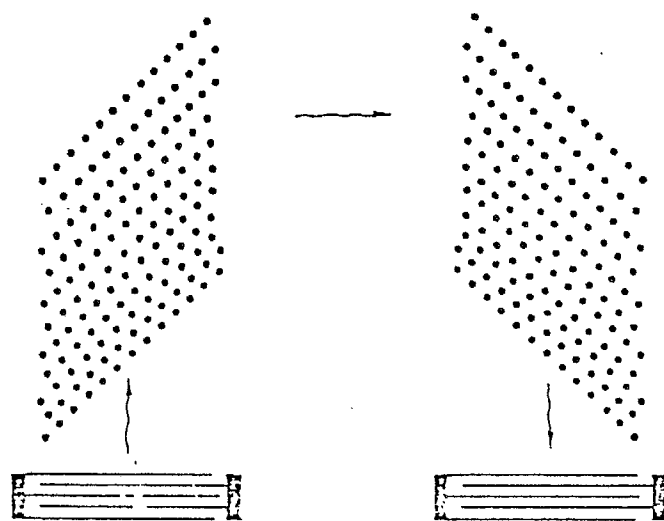


Fig. 6 Typical layout of a Reflective Dot Array Device

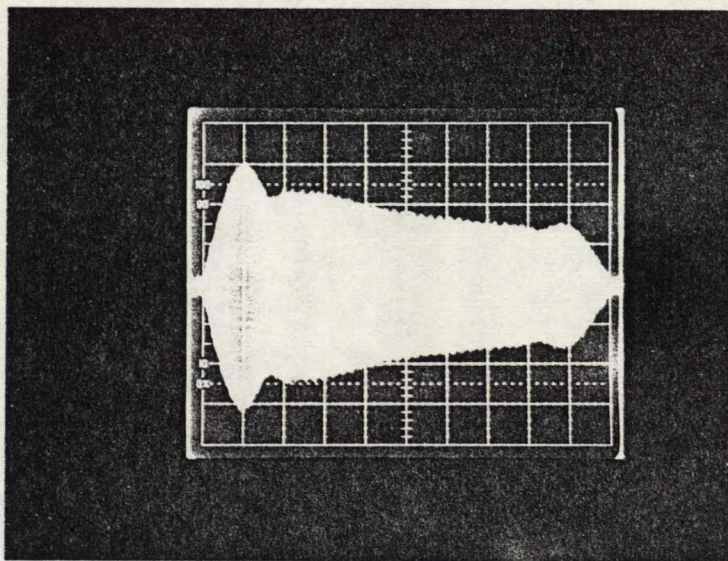


Fig. 7      Impulse    response of  
             GRAC2 device  $1\mu\text{s}/\text{div}$



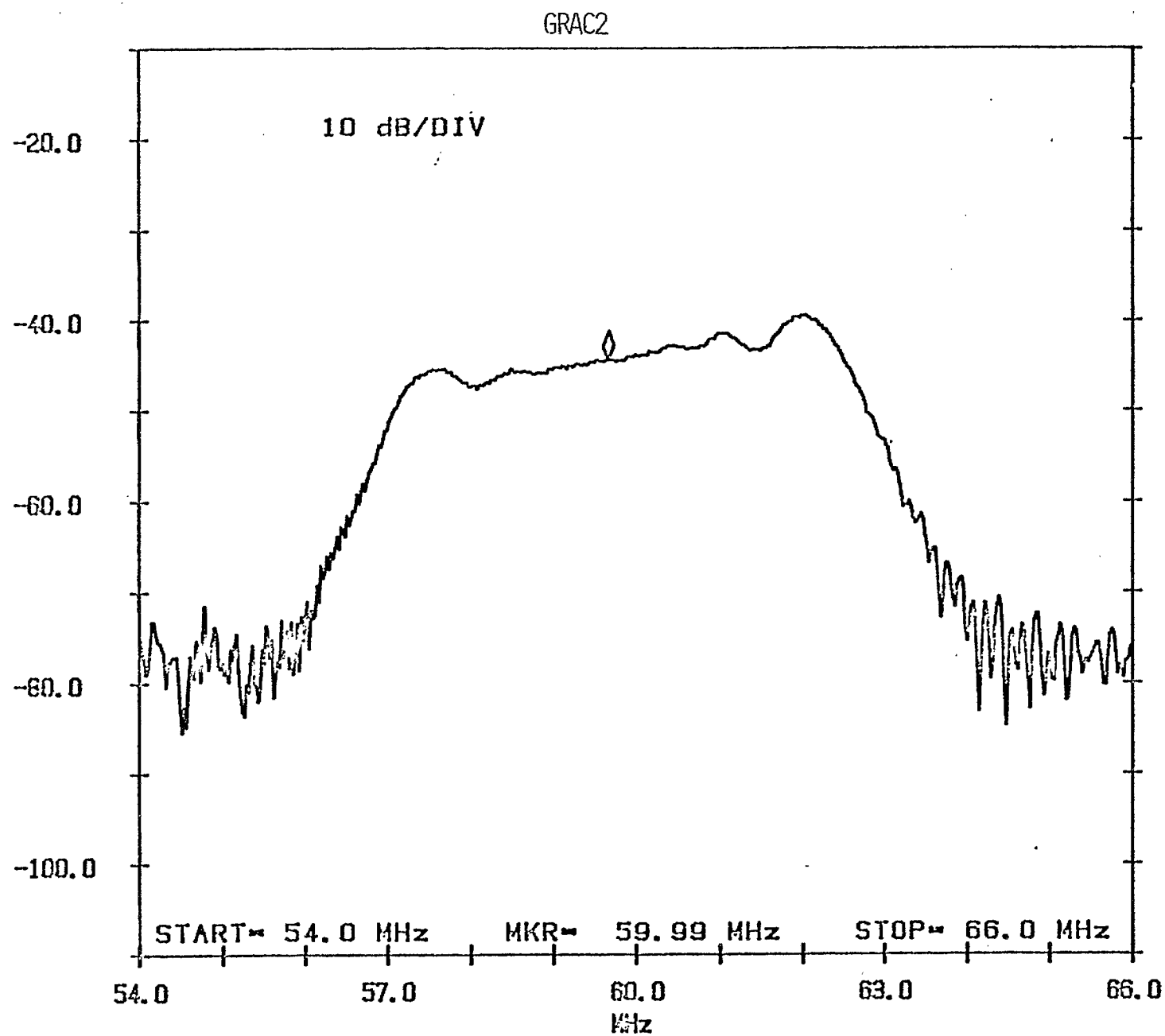


Fig. 8 Frequency response of untuned GRAC2

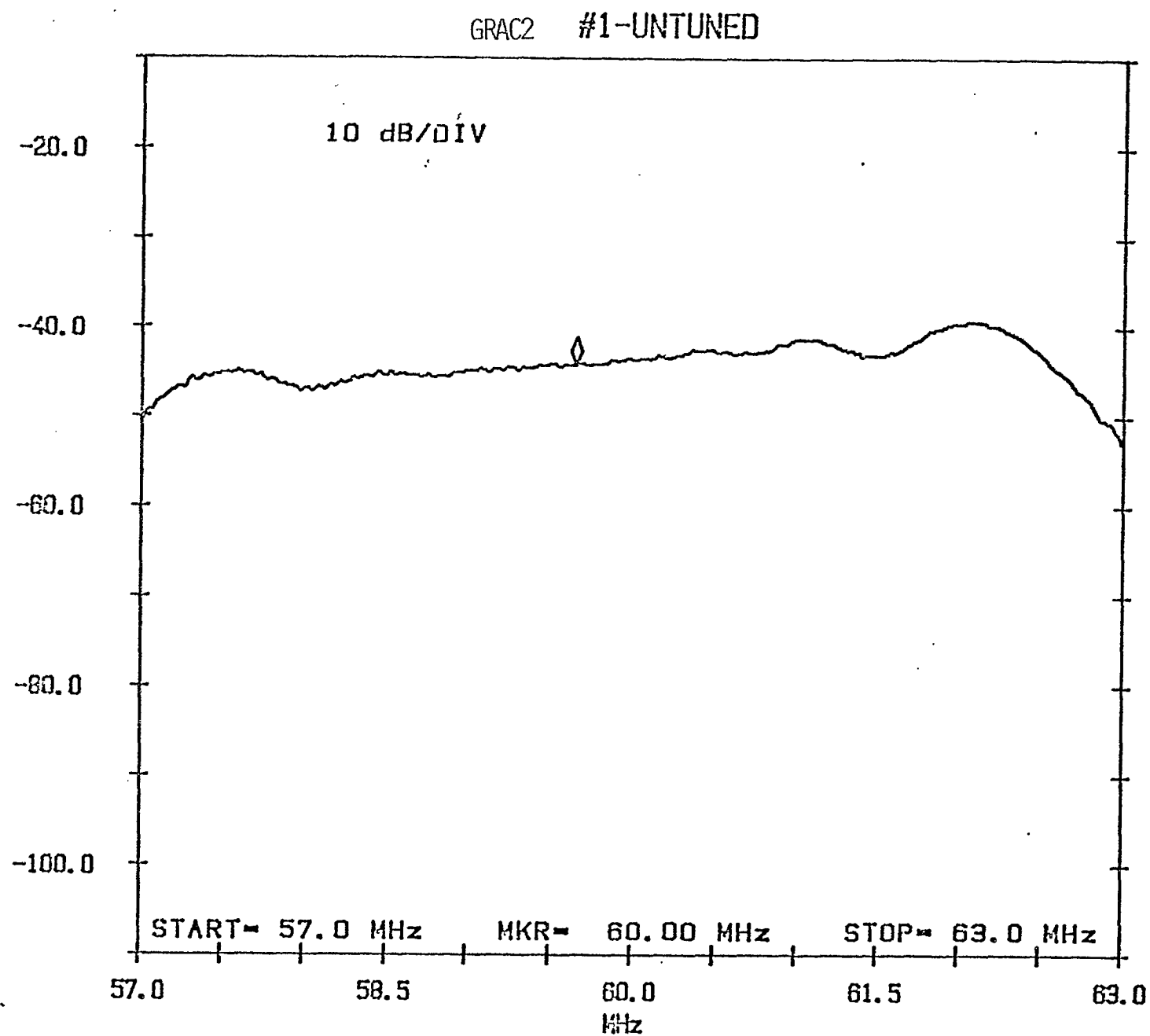


Fig. 9 Frequency response of untuned GRAC2

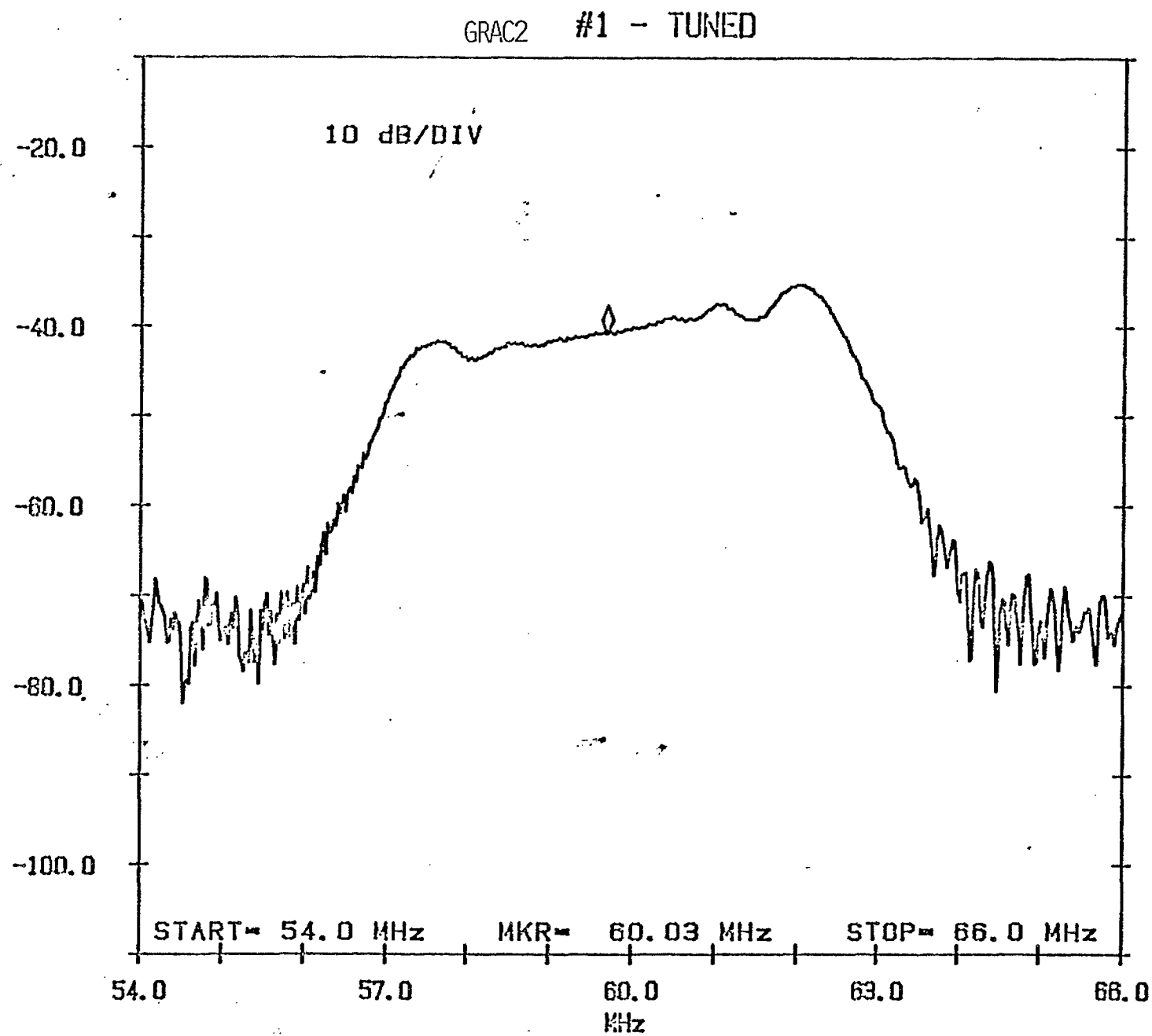


Fig. 10 Frequency response of series tuned GRAC2



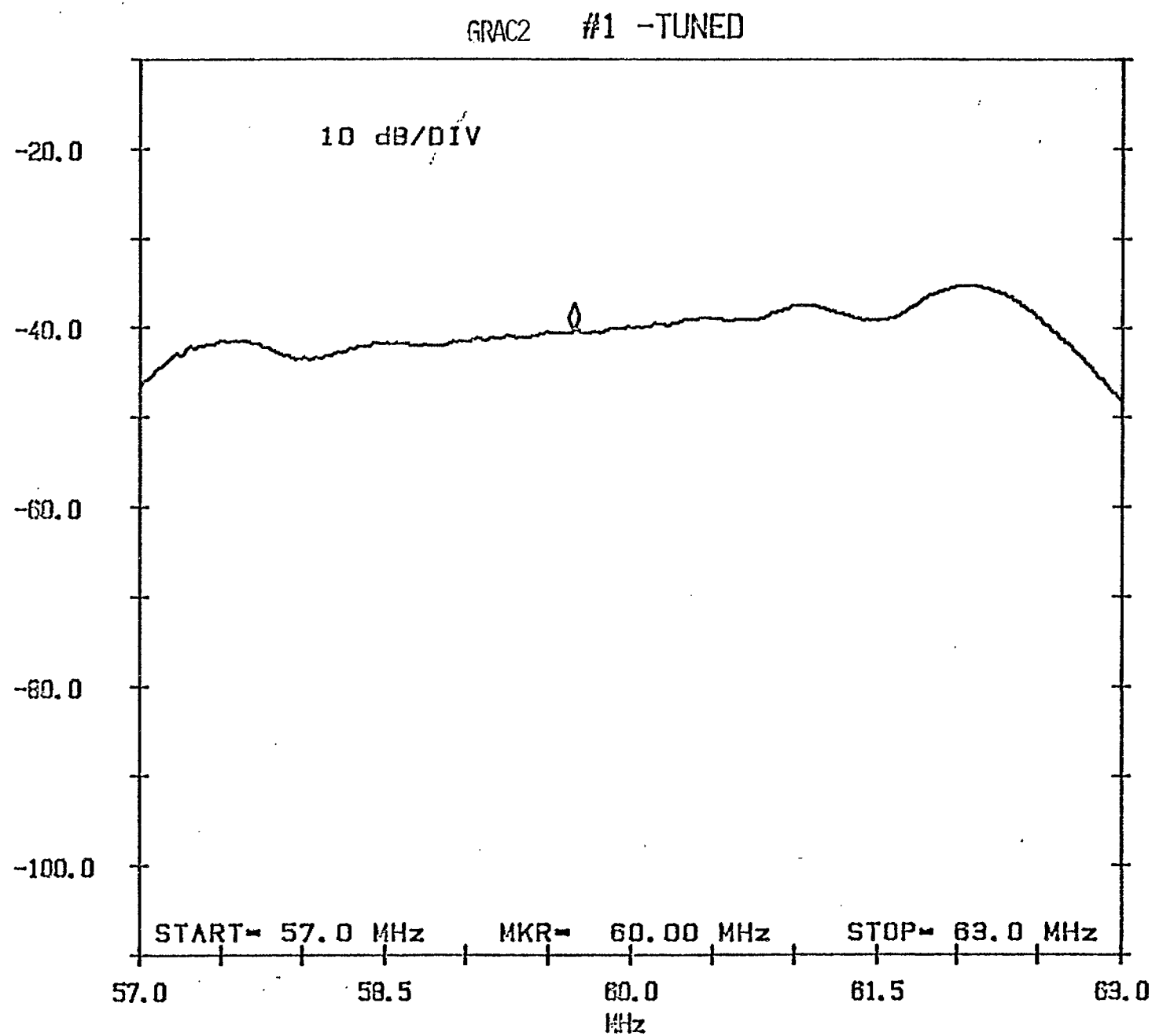


Fig. 11 Frequency response of series tuned GRAC2

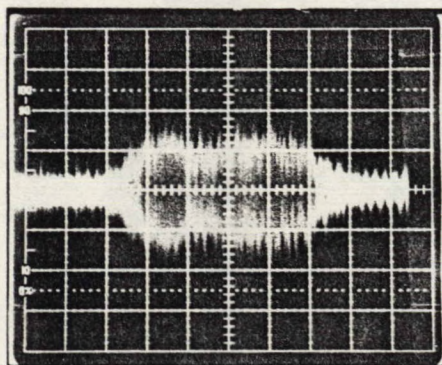


Fig. 12    Impulse response  
            MRAC1 #1  
            2 $\mu$ s/div



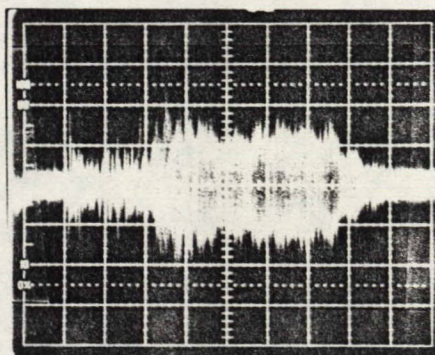


Fig. 13      Impulse response  
MRAC1 #2    2  $\mu$ s/div



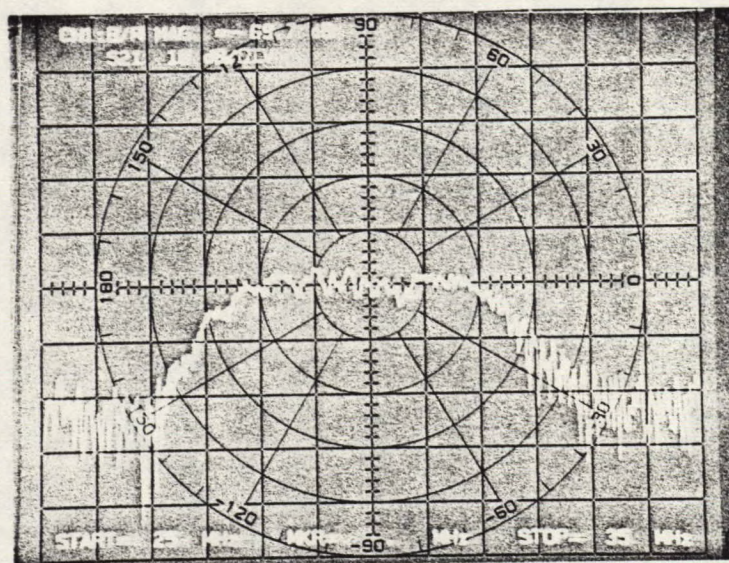


Fig. 14 Frequency response  
MRAC1 #1



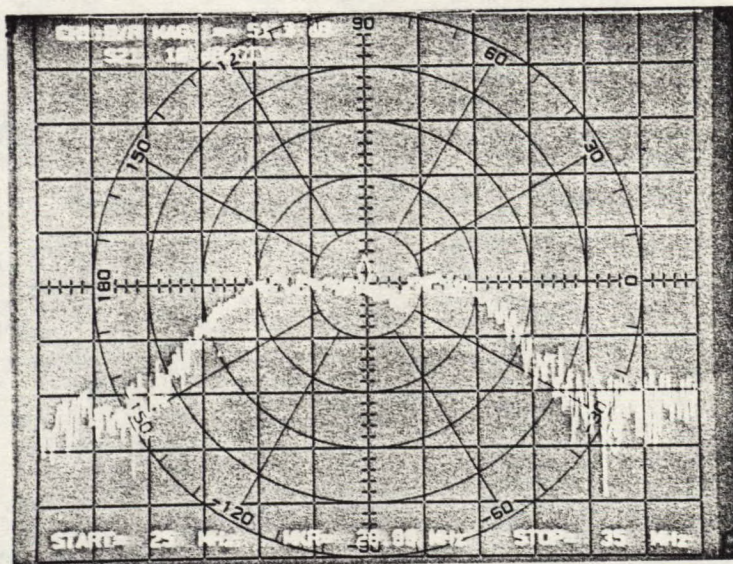


Fig. 15      Frequency Response  
MRAC1 #2



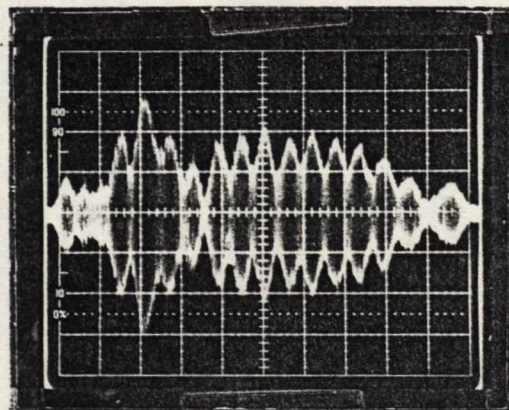


Fig. 16      Impulse response  
MRAC2      1  $\mu$ s/div



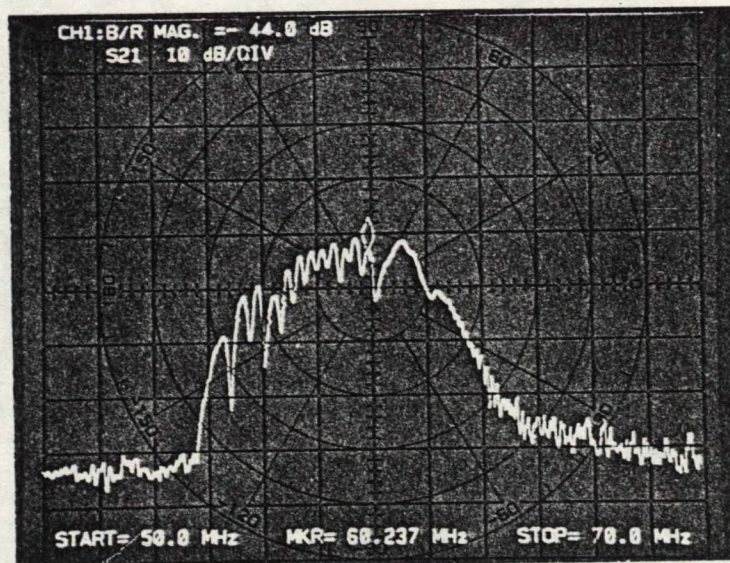


Fig. 17 Frequency response  
MRAC2



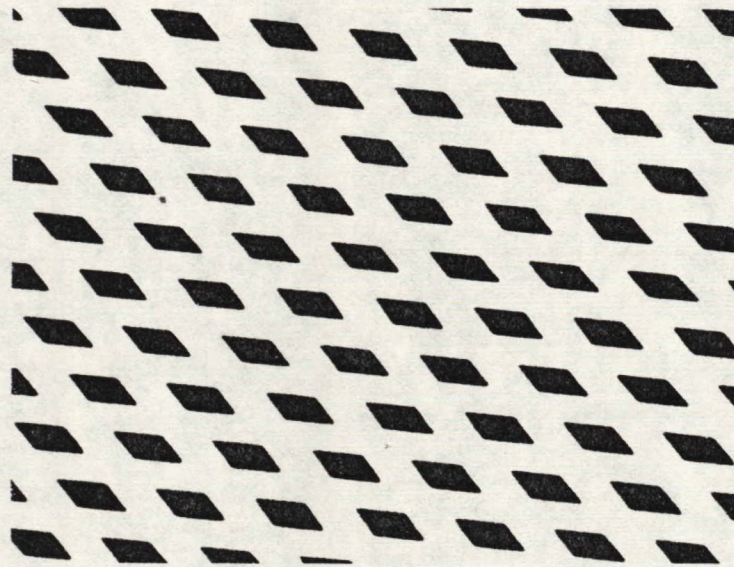


Fig. 18    Section of the DRAC Mask  
Dark areas - metallic dots  
Clear areas - substrate surface



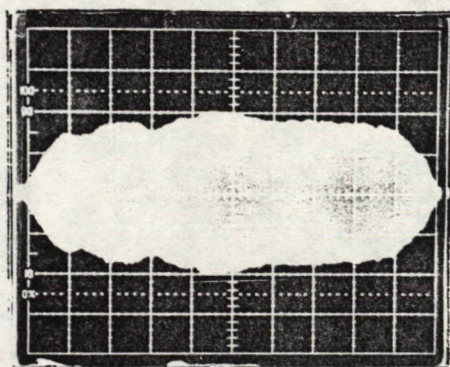


Fig. 19 Impulse Response  
DRAC2 - 12000 Å device  
1 $\mu$ s/div



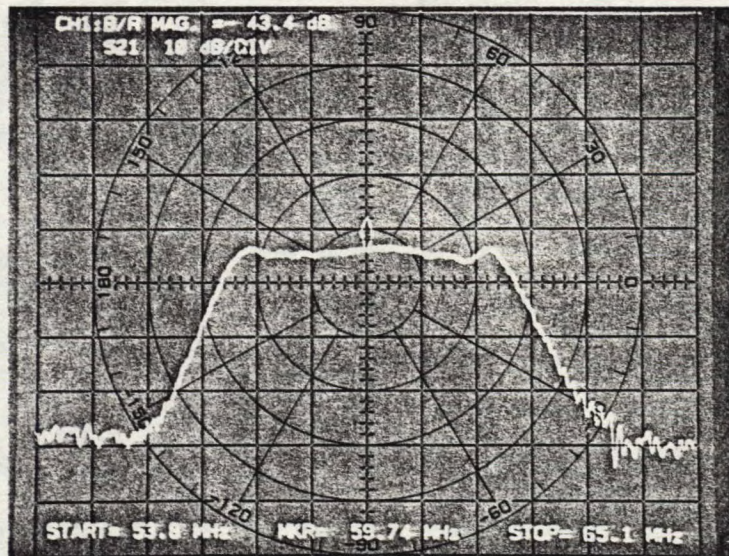


Fig. 20 Frequency Response  
DRAC2 - 12000 A device



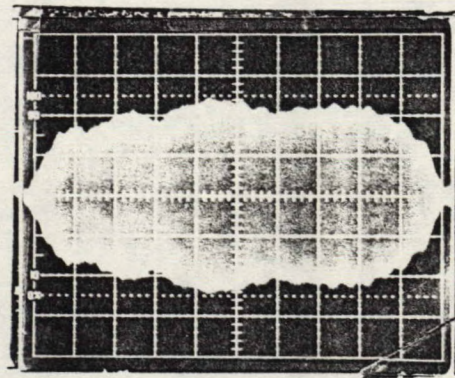


Fig. 21 Impulse Response  
DRAC2 - 7000 Å device



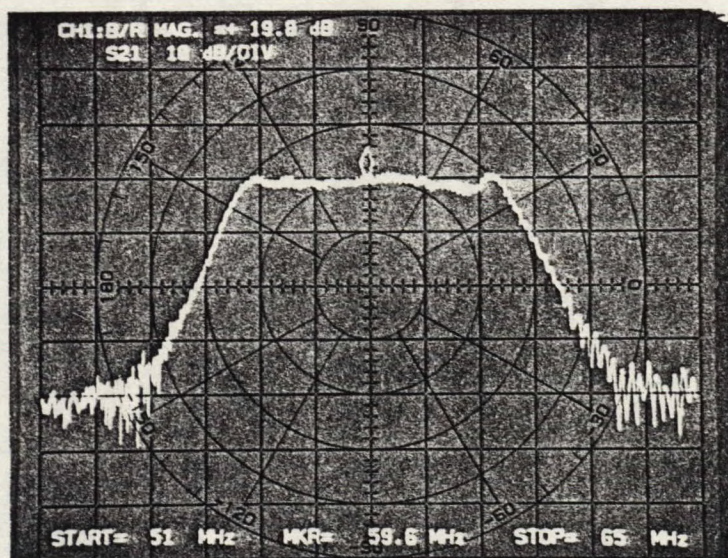


Fig. 22 Frequency Response  
DRAC2 - 7000 Å device



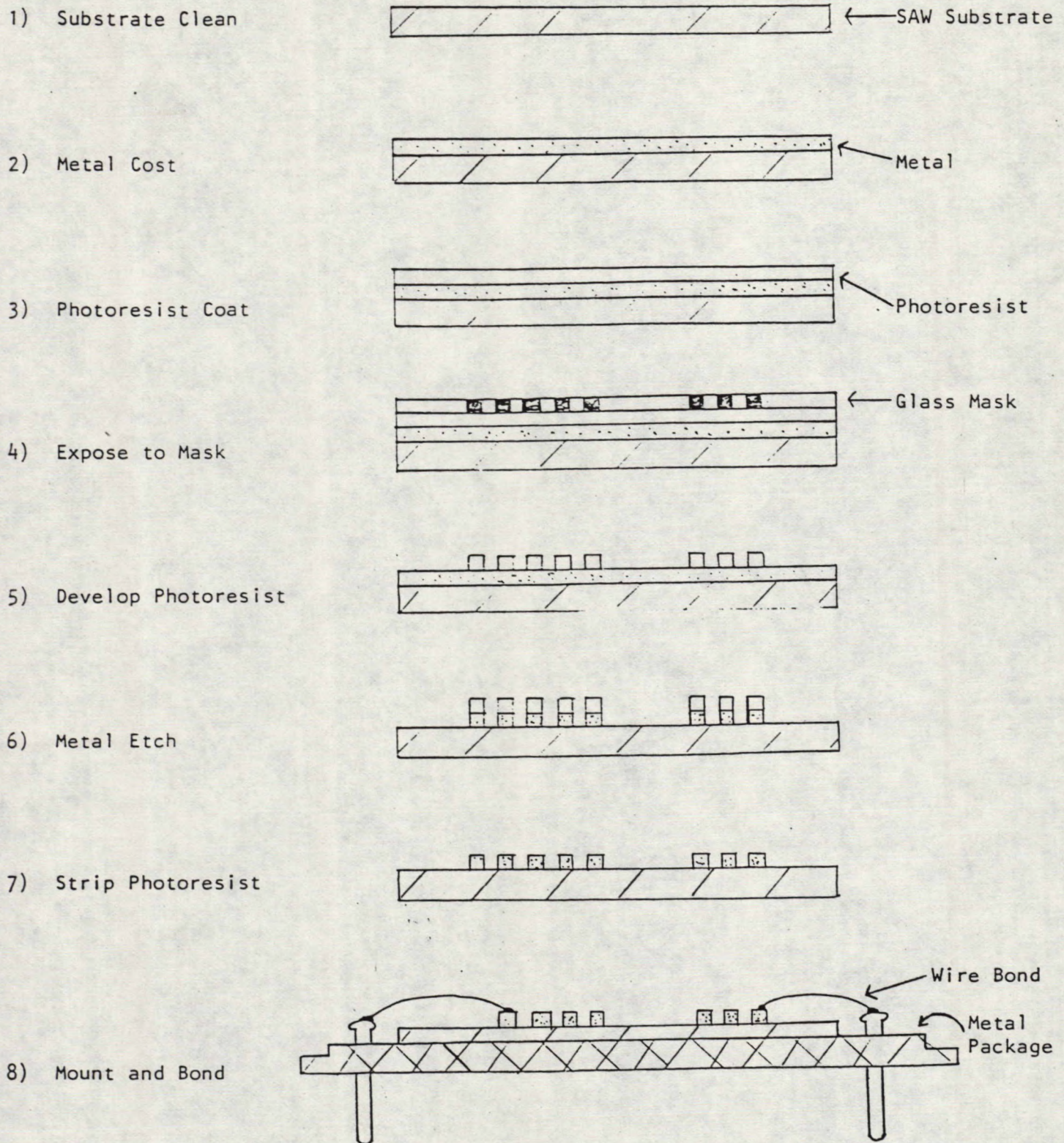


FIG. 23 Steps Required for the Fabrication of MRAC's and DRAC's



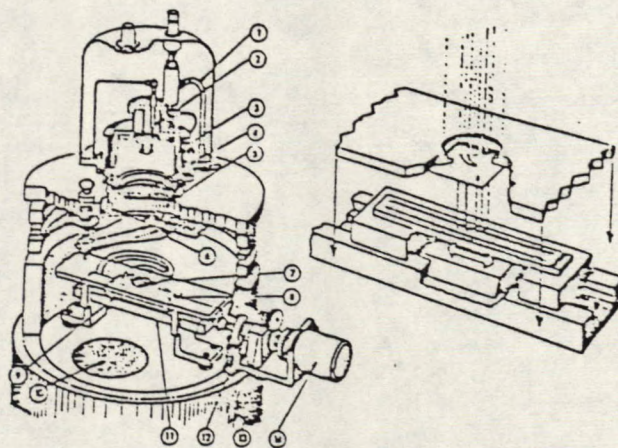


Fig. 24 Ion beam etching apparatus: (1) argon gas inlet, (2) arc filament, (3) magnet, (4) ion-beam extraction grids, (5) neutralizing filament, (6) shutter, (7) chevron aperture, (8) RAC substrate, (9) water - cooled sample platform, (10) pumping port, (11) micrometer-slide assembly, (12) rotary-motion high vacuum feedthrough, (13) position indicator, (14) stepping motor.



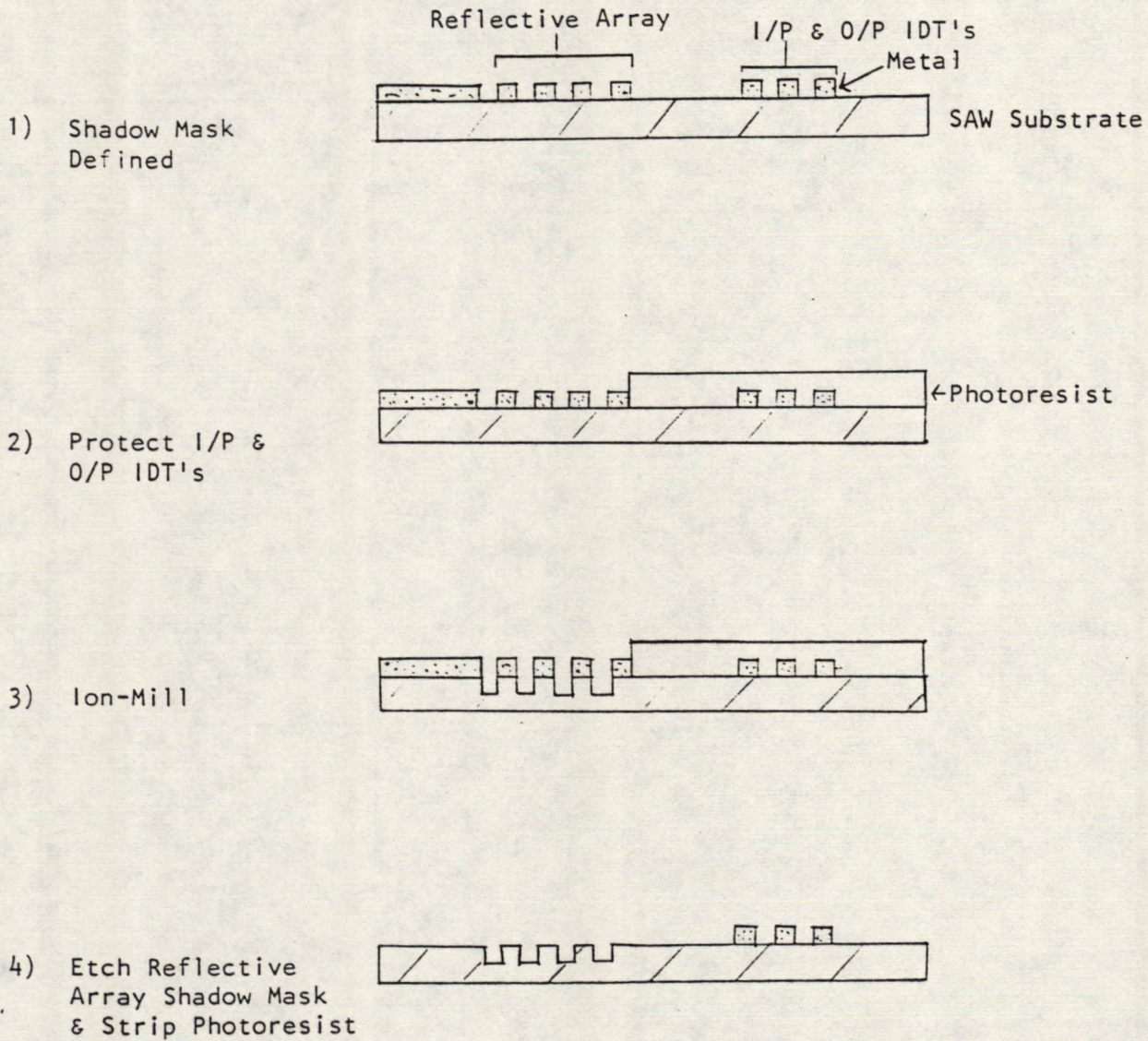


FIG. 25 Extra Fabrication Steps Needed for GRAC Devices

INDUSTRY CANADA / INDUSTRIE CANADA



208159



**COM DEV PRODUCTS AND SERVICES  
FOR  
COMMUNICATIONS AND RADAR SYSTEMS**

**HIGH POWER MICROWAVE PRODUCTS**

- High Power Filters, Diplexers, Combiners
- High Power Isolators, Circulators
- High Power Couplers, Splitters, Terminations
- Low Loss Transmit Reject Filters
- Variable Power Combiners
- High Power Antenna Co-polarized Diplexers
- Amplitude Equalizers
- Group Delay Equalizers

**COMMUNICATIONS SATELLITE PRODUCTS**

- Low Loss, High Order Dual Mode Output Multiplexers
- Beam Switching and Beam Reconfiguring Networks
- High Power Microwave Components and Subsystems
- Waveguide and Coax Isolators, Circulators
- Low Pass Receive Band and Harmonic Band Reject Filters
- Low Loss Preselect Filters
- Group Delay and Amplitude Equalized Input Multiplexers
- Waveguide to SMA Adaptors and Monitor Couplers
- Telemetry and Command Filters
- Variable Power Dividers

**CONSULTING SERVICES**

- Conceptual, hardware and systems of Microwave transponders and Communications Subsystems for Communications Satellites.
- Tradeoff analyses, layout and hardware design of high power combining and multiplexing networks for Satellite Earth Terminals.
- All software and hardware aspects of devices and subsystems involving microwave filtering networks and ferrite devices for both terrestrial and satellite communications systems.



**COM DEV LTD.**

155 SHELDON DRIVE,  
CAMBRIDGE, ONTARIO, CANADA N1R 7H6  
TEL.: (519) 622-2300 • TWX: 610-366-3164

MICROWAVE DEVICES AND SUBSYSTEMS FOR TERRESTRIAL AND SATELLITE COMMUNICATIONS