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THIN FILM MONOLITHIC BYPASS FILTERS

NAVAL AIR DEVELOPMENT CENTER

WARMINSTER, PA. 18974

CONTRACT N62269 - 80-C-0024

FINAL REPORT

HULL CORPORATION, THINCO DIVISION
BYBERRY ROAD
HATBORO, PA. 19040

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

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Monolithic Thin Film Bypass Filters consisting of one inductor and one capacitor have been fabricated using vacuum deposition techniques. The inductor and the capacitor are formed at the same time by depositing alternate layers of metal and dielectric materials. The inductor and the capacitor are interconnected to form a three terminal device. Two sizes of Bypass Filters, designated as LC-55 and LC-100 having inductance value ranging from 35 to 1,100 nanohenries and capacitance value ranging from 11.5 to

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510 picofarads have been constructed. It has been shown that the values of inductance and capacitance of a Bypass Filter can be varied almost independently by changing the thickness of the dielectric deposited. Measurements of the electrical parameters of the inductor and the capacitor individually as well as the frequency characteristics of the device functioning as a Lowpass or Highpass filter have been conducted.

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FINAL REPORT

1.0 INTRODUCTION

The Hull Corporation, Thinco Division, has been awarded a contract by the Naval Air Development Center to develop and fabricate thin film monolithic bypass filters consisting of one inductor and one capacitor deposited simultaneously on the substrate. The inductor is connected to the capacitor to form a three terminal network. Two sizes of the inductors with comparable size of associated capacitors have been developed and fabricated. The inductance ranges from 30 nanohenries to 1.1 microhenries and the capacitances ranges from 15 to 500 picofarads. In this fabrication method, the inductors are formed in steps of one-half turn, while an electrode of the capacitor is formed simultaneously. One terminal of the capacitor is connected to the inductor while being formed, such that the completed unit is a three terminal device. The dielectric layer between two electrodes of the capacitor is deposited simultaneously as the insulating layer between turns of the winding of the inductor. The most important technique which has been developed in this project, was the ability to vary the values of capacitance and inductance independently so that for a given set of deposition masks, the ratio of inductance and capacitance can be varied at will.

2.0 METHOD OF FABRICATION

In the fabrication of the monolithic bypass filter, an electrode of the capacitance is deposited at the same time as a half-turn of the inductor. Thus, the odd half-turns of the inductor are deposited along with one group of the electrodes of the capacitor and the even half-turns of the inductor are deposited along with the other group of electrodes of the capacitor. The insulating layer for each half-turn of the inductor is also deposited at the same time as the dielectric layer between two adjacent electrodes of the capacitor. The deposition sequence is illustrated in Figure 2.0-1(1) through Figure 2.0-1(6). The light areas represent metal depositions, and the dark areas represent dielectric depositions. Aluminum was used in the metal deposition and the Thinco T-3 material was used in the dielectric deposition which was selected for its low dielectric loss at high frequencies.

The sequence of deposition, as shown in Figure 2.0-1(1) through Figure 2.0-1(6), is summarized as follows:

Step 1. Deposition of metal for the first half-turn of the inductor and the first electrode of the capacitor. The area which joins the inductor and the capacitor serves also as the common termination of the inductor and the capacitor (Mask No. 1).

Step 2. Deposition of the first dielectric layer over the first half-turn of the inductor and the first dielectric layer of the capacitor (Mask No. 2).

Step 3. Deposition of the second half-turn of the inductor joining the first half-turn. At the same time the second electrode of the capacitor is also deposited over the first dielectric layer. Two masks are provided for this step which are identical except having different width of the second electrode for the capacitor. This is needed to produce the range of capacitance required. (Masks Nos. 3A and 3B).

Step 4. Deposition of the second dielectric over the second half-turn of the inductor and the second dielectric layer of the capacitor (Mask No. 4).

Step 5. Deposition of the third half-turn of the inductor and the third electrode of the capacitor. The third half-turn of the inductor joins the second half-turn of the inductor. The third electrode of the capacitor connects to the first electrode of the capacitor (Mask No. 5).

Step 6. Repeat Step 2 if the total number of turns of the inductor is more than 1 1/2.

Step 7. Repeat Step 3 if the total number of turns of the inductor is more than 1 1/2.

Step 8. Deposition of the last half-turn of the inductor with the end termination and the last electrode of the capacitor (Mask No. 6).

Step 9. Deposition dielectric to cover the entire inductor and the capacitor except the three termination pads using Masks No. 2 and No. 4.

The metal and dielectric patterns were deposited onto a 2" x 2" x .01" alumina or 2" x 2" x .025" ferrite substrate through six different masks as indicated above. Each mask contains an array of identical patterns of metal or dielecric. There are 126 LC-100 bypass filters or 330 LC-55 bypass filters on each substrate. Precise registration must be maintained of the mask to the substrate by means of guide pins. The six masks were mounted on a round rotating carrier in a NRC 3176S vacuum system using a stainless steel bell jar 25 inches in diameter by 30 inches high. Two movable crucibles were used, one for aluminum and the other for the dielectric. Feeding mechanisms were provided to feed the aluminum wire and dielectric chips to replenish the materials in the crucibles during depositions. The entire array of bypass filters was completed without any interruption of the vacuum system.

An electron beam system (Airco-Temescal CV-14 unit) was used for the energy source of deposition which is capable of producing a maximum beam power of 14 kw. To reduce the spreading of the deposited material, the masks must be kept at close contact with the substrate. Magnetic stainless steel masks were used in conjection with a permanent magnet assembly for pulling the mask against the substrate tightly. The thickness of depositions was monitored by quartz crystal rate and thickness controllers.

The array of bypass filters was heat-treated at 450° C in a dry nitrogen atmosphere after the depositions were completed to reduce the electrical resistances at the metal interfaces and relieve the mechanical stresses in the inductors and capacitors. The substrate was then cut to individual bypass filter chips by a dicing saw. A photomicrograph of a completed LC-55 bypass filter is shown in Figure 2.0-2.

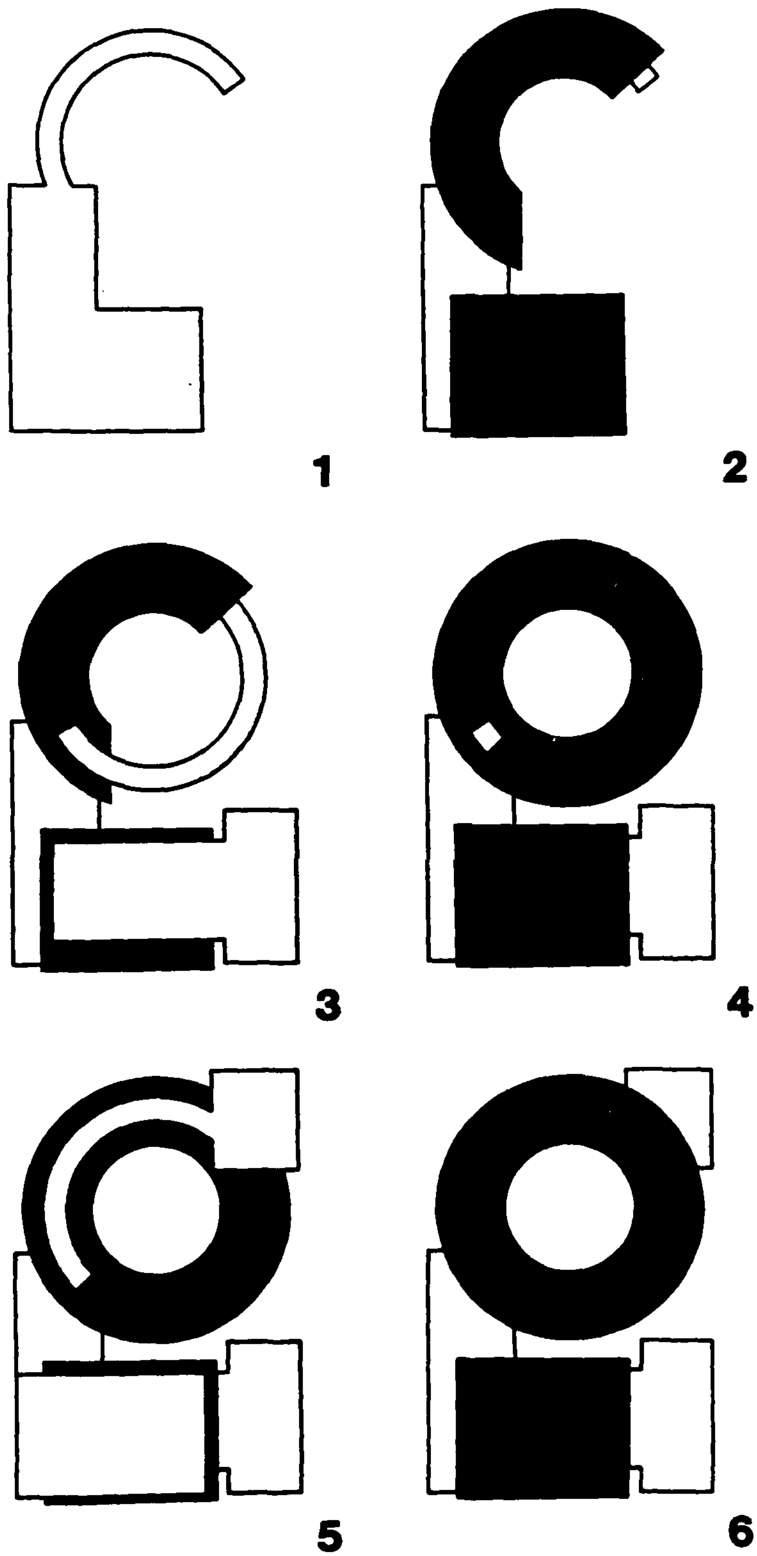

Figure 2.0-1 - Deposition Sequence of Bypass Filter

Figure 2.0-2 - Photomicrograph of LC55 Bypass Filter

3.0 INDEPENDENT VARIATIONS IN INDUCTANCE AND CAPACITANCE

The inductance and capacitance of the inductor and capacitor in the monolithic bypass filter can be varied independently by changing the thickness of the dielectric deposited. This is due to the fact that the capacitance is inversely proportional to the thickness of the dielectric layer which has a much smaller effect on the inductance. Therefore, the capacitance can be varied without changing the value of the inductance appreciably. The inductance is varied by changing the number of turns of the winding which determines also the number of electrodes of the capacitor. The capacitance, however, can be kept constant or changed at a different ratio as that of the inductance by adjusting the thickness of the dielectric. There is, of course, a practical limitation of the thickness of the dielectric deposition to be deposited.

3.1 INDUCTANCE FACTORS

The inductance of a circular thin film inductor can be calculated by using Nagaoka's formula with tables of constants given by Grover[1]. The equation is:

$$L = 2\pi 2a \left(\frac{2a}{b}\right) N^2 K \text{ nanohenries} \qquad (3.1\text{-}1)$$

1. Grover F.W., Inductance Calculations, D. VanNostrand Co., New York 1946

Where L = inductance in nanohenries

a = geometric mean radius of the winding in cm

b = length of the winding in cm

N = number of turns

K = factor of end effects

The factor of end effects, K is a function of the ratio 2a/b and is given by the following series;

$$K = \frac{2\beta}{\pi} [\ell n \frac{4}{\beta} - \frac{1}{2}) + \frac{\beta^2}{8} (\ell n \frac{4}{\beta} + \frac{1}{8}) - \frac{\beta^4}{64} (\ell n \frac{4}{\beta} - \frac{2}{3}) +$$

$$\frac{5}{1024} \beta^6 (\ell n \frac{4}{\beta} - \frac{109}{120}) \ldots] \qquad (3.1 - 2)$$

in which $\beta = b/2a$. This series converges rapidly and two terms are usually sufficient. The geometrical mean radius, a is obtained from the following relation:

$$\ell n\ a = \ell n\ \gamma_2 - \ell n \xi \qquad (3.1 - 3)$$

where γ_2 is the outer radius (in cm) and ξ is given in a table by Grover[1]. The actual inductance measured at 50 MHz on a Hewlett-Packard Model 4342A Q-Meter is lower than the calculated values by a more or less constant factor which can be contributed to the eddy current induced in the flat winding producing a magnetic field parallel to the axis of the inductor. The inductance equation can be written as:

$$L = 4\pi a N^2 [\ell n \frac{8a}{6} - \frac{1}{2}) + \frac{b^2}{32a^2} (\ell n \frac{8a}{b} + \frac{1}{8}) - \frac{b^4}{1024a^4}$$

$$(\ell n \frac{8a}{b} - \frac{2}{3}) + \ldots] \text{ nanohenries} \qquad (3.1 - 4)$$

Since $a >> b$

the contributions of the terms of the series except the first are relatively small. The inductance is approximately

$$L = 4\pi a N^2 (\ell n \frac{8a}{b} - \frac{1}{2}) \text{ nanohenries} \qquad (3.1 - 5)$$

3.2 CAPACITANCE FACTORS

The capacitance of the multilayer parallel capacitor is given by

$$C = 5.705 \frac{\varepsilon A}{t} (2N-1) \times 10^{-3} \text{ picofarads} \qquad (3.2 - 1)$$

where C = capacitance in picofarads

A = area of electrode in square mils

t = thickness of dielectric in microns

N = number of turns of the inductor in the bypass filter

ε = dielectric constant of the dielectric

For a given mask set and a given number of turns of the inductor, the capacitance of the capacitor in the bypass filter is inversely proportional to the thickness of the dielectric deposition.

3.3 VARIATIONS IN INDUCTANCE AND CAPACITANCE

For a given number of turns in the inductor of a given size the inductance decreases when the thickness of the dielectric deposition is increased while the thickness of metal deposition remains the same. From equation (3.1 - 5) in Section 3.1 the inductance increases when the thickness of the dielectric layer is decreased. From equation (3.2 - 1) in Section 3.2 the capacitance increases when the thickness of the dielectric layer is decreased. The percentage change in inductance, however, is much less than the percentage increase in capacitance. This fact can be illustrated by the following numerical example.

LC-55 Bypass Filter

No. of turns of the inductor, $N = 5.5$

Thickness of metallization, $tm = 3$ microns

Thickness of dielectric layer, $td = 4$ microns

No. of electrodes of the capacitor, $2N = 11$

Inside radius of inductor, $\gamma_1 = .0572$ cm

Outside radius of inductor, $\gamma_2 = .0699$ cm

Area of capacitor electrode = 888 mil^2

$\gamma_1/\gamma_2 = .8182$

From Table 4 (p. 23, Grover[1]) $\ell n\xi = .0603$

From equation (3.1 - 3)

$\ell na = \ell n\ \gamma_2 - \ell n\xi = \ell n\ .0699 - .0603$

$a = .0658$ cm

$b = Np = N(tm + td) = 5.5 \times (3 + 4) \times 10^{-4} = 3.85 \times 10^{-3}$ cm

From equation (3.1 - 5) the inductance is

$$L = 4\pi a N^2 \left(\ell n \frac{8a}{b} - \frac{1}{2}\right) = 4\pi \times .0658 \times (5.5)^2 \times$$

$$\left(\ell n \frac{8 \times .0658}{3.85 \times 10^{-3}} - 0.5\right)$$

$L = 110.45$ nH

From equation (3.2 -1) the capacitance is

$$C = 5.705 \frac{\varepsilon A}{t} (2N - 1) \times 10^{-3} \text{ pF}$$

$$= 5.705 \frac{4.3 \times 888}{4} \times (11-1) \times 10^{-3}$$

$$= 54.41 \text{ pF}$$

(ε = dielectric constant of the dielectric used = 4.3)

If the thickness of the dielectric layer is reduced to 2 microns, then

$$b = Np = 5.5 \times (3 + 2) \times 10^{-6} = 2.75 \times 10^{-3} \text{ cm}$$

$$L = 118.86 \text{ nH}$$

$$C = 108.82 \text{ pF}$$

Therefore, an increase of 100% in the capacitance is accompanied by an increase of 9% in the inductance. If it is required, the thickness of the metallization can be increased by 2 microns while the dielectric is decreased by 2 microns so that the pitch p is unchanged. In this manner the capacitance is doubled while the inductance is unchanged.

The example given above demonstrates the fact that the inductance and the capacitance of a monolithic filter can be varied independently for a given set of masks. This is a very important factor which makes the integration of LC networks feasible.

In order to maintain the thickness of the metal and dielectric within certain practical limits two different masks for the second metal deposition were used. These two masks designated as Mask No. 3A and 3B are identical except that the areas of the second (and all the even number) electrode of the capacitor for the LC-100 bypass filters are .077 x .042 in. and .077 x .012 in. respectively. The other five (5) masks in the set are unchanged. The corresponding masks for the LC-55 bypass filters have areas of .039 x .026 in. and .039 x .013 in. respectively.

3.4 ENHANCEMENT OF INDUCTANCE USING FERRITE SUBSTRATE

To obtain the high values of inductance values required magnetic substrate was used. By depositing the inductors and capacitors directly on ferrite instead of alumina substrate, the inductance was increased but the capacitance of the capacitor was not affected. A planar hexagonal ferrite substrate about .025 in. thick was used which increased the inductance approximately 60%. Use of ferrite substrate provides yet another way to vary the inductance and capacitance of the bypass filters independently.

4.0 BYPASS FILTERS FABRICATED

Bypass filters of two different sizes were fabricated which are designated as LC55 and LC100 using alumina substrate, and LC55F and LC100F using ferrite substrate.

4.1 PHYSICAL DIMENSIONS OF BYPASS FILTERS

The dimensions of the bypass filter of various types are listed below.

Bypass Filter Type	LC55	LC100
Substrate Dimensions	.069 x .108 x .01 in.	.122 x .177 x .01
Outside Diameter of Inductor	.055 in	.100 in.
Area of Capacitor (Maximum)	.039 x .026 in	.077 x .042 in.
Substrate Material	Alumina	Alumina
Bypass Filter Type	LC55F	LC55F
Substrate Dimensions	.069 x .108 x .025 in.	.122 x .177 x .025
Outside Diameter of Inductor	.055 in.	.100 in.
Area of Capacitor (Maximum)	.039 x .026 in.	.077 x .042 in.
Substrate Material	Ferrite	Ferrite

4.2 ELECTRICAL PARAMETERS OF BYPASS FILTERS

The values of inductance and capacitance of the various types of bypass filters fabricated and delivered to the Naval Air Development Center are listed in the following.

Filter Type	Inductance, nH	Capacitance, pF
LC 55	35	11.5
LC 55	225	110
LC 55F	380	144
LC 100F	230	51
LC 100F	650	300
LC 100F	1,100	510

The variation of the values of inductance of the inductors in the bypass filter within the substrate was measured to be approximately 2 percent whereas the variation of the capacitance within a given substrate was about 7 percent. Investigation of the causes of the relatively large variation in capacitance indicated that the slight misalignment of the edges of the two electrodes of the capacitor was the main factor. This effect was more pronounced for the mask having the narrower capacitor electrode where the edge misalignment constituted a large percentage change in capacitance. Such slight misalignment also existed in the winding of the inductor but the effect on inductance was much smaller.

5.0 MEASUREMENT OF THE PARAMETERS OF THE BYPASS FILTERS

The components of the bypass filter fabricated have been measured individually to determine the uniformity of the values and the frequency characteristics of the bypass filter as a whole have also been measured.

5.1 MEASUREMENT OF INDIVIDUAL COMPONENTS

The inductor and the capacitor of the bypass filter were measured individually on a Hewlett-Packard Model 4342A Q-Meter. The inductance was measured at 50 MHz using a series work coil for inductances less than 250 nH and directly for inductance greater than 250 nH. The capacitance was measured by substitution method using the calibrated variable capacitor in the Q-Meter. The self-resonant frequency and the Q-factor of the inductor were measured on the Sweep Frequency Tester built by Thinco. The Q-factor of the capacitance was measured on the Q-Meter which has a maximum measuring frequency of 70 MHz. A higher frequency measurement could be made on a Boonton Radio Company RX-Meter which has a maximum frequency of 250 MHz. The maximum measureable capacitance, however, is limited to 20 pF.

The parameters of the inductors and capacitors of various bypass filter fabricated are given in Table 5.1 - 1.

5.2 MEASUREMENT OF FREQUENCY RESPONSE OF BYPASS FILTERS AS LOW-PASS OR HIGH-PASS FILTERS

The insertion loss of the bypass filters connected as low-pass and high-pass filters have been measured on a Hewlett-Packard Model 8507A Network Analyzer. The schematic diagram of the connections of the bypass filter in the measurements are shown in:

Figure 5.2 - 1 - Single Section Low-Pass Filter

Figure 5.2 - 2 - Single Section High-Pass Filter

Figure 5.2 - 3 - Double Section Low-Pass Filter

The frequency response (insertion loss vs. frequency) of the various filters are given by the output plots of the network analyzer and are shown in the following figures.

Figure 5.2 - 4 - Single Section Low-Pass Filter, L = 35 nH, C = 11.5 pF

Figure 5.2 - 5 - Single Section Low-Pass Filter, L = 225 nH, C = 110 pF

Figure 5.2 - 6 - Single Section Low-Pass Filter, L = 300 nH, C = 144 pF

Figure 5.2 - 7 - Single Section Low-Pass Filter, L = 230 nH, C = 51 pF

Figure 5.2 - 8 - Single Section Low-Pass Filter, L = 650 nH, C = 300 pF

Figure 5.2 - 9 - Single Section Low-Pass Filter, L =1100 nH, C = 510 pF

Figure 5.2 -10 - Single Section High-Pass Filter L = 35 nH, C = 11.5 pF

Figure 5.2 -11 - Single Section High-Pass Filter L = 230 nH, C = 51 pF

Figure 5.2 -12 - Double Section Low-Pass Filter, L = 35 nH, C = 11.5 pF

Figure 5.2 -13 - Double Section Low-Pass Filter, L = 225 nH, C = 110 pF

Figure 5.2 -14 - Double Section Low-Pass Filter, L =1100 nH, C = 510 pF

TABLE 5.1-1: MEASURED PARAMETERS OF INDIVIDUAL COMPONENTS

Bypass Filter Type	No. of turns of Inductor	Inductance nH	No. of Electrodes of Capacitor	Capacitance pF	fo MHz	QL@ MHz	Qc@ MHz
LC-55	3 1/2	35	7	11.5	980	30/980	265/250 960/1.0
LC-55	9 1/2	225	19	110	352	23/352	615/1.0
LC-55F*	10 1/2	380	21	144	285	31/285	425/1.0
LC-100F*	5 1/2	230	11	51	220	38/150	192/1.0
LC-100F*	9 1/2	650	19	298	143	25/143	240/1.0
LC-100F*	12 1/2	1,100	25	510	104	37/56	269/1.0

* Ferrite Substrate

Q_L Intrinsic Q-Factor of Inductor

fo Self-Resonant frequency of inductor

Qc Q-Factor of Capacitor

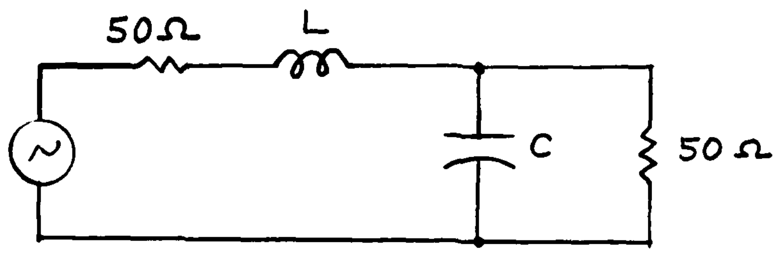

Figure 5.2-1 - Single Section Low-Pass Filter

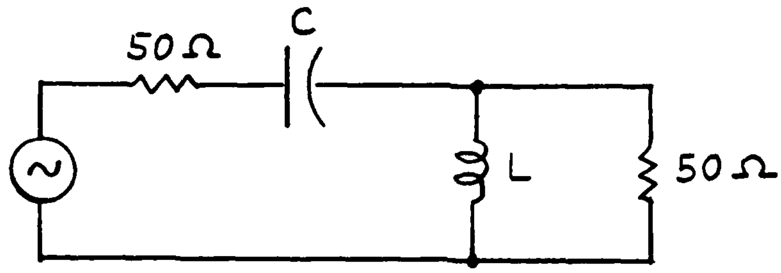

Figure 5.2-2 - Single Section High-Pass Filter

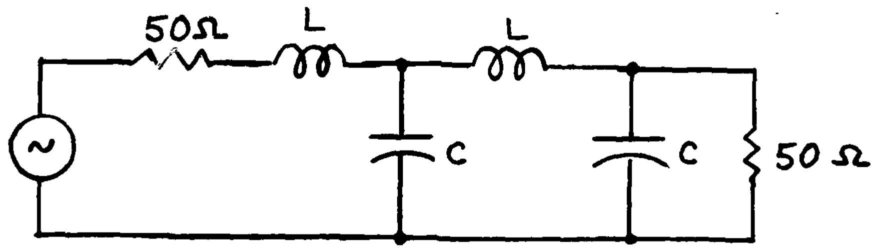

Figure 5.2-3 - Double Section Low-Pass Filter

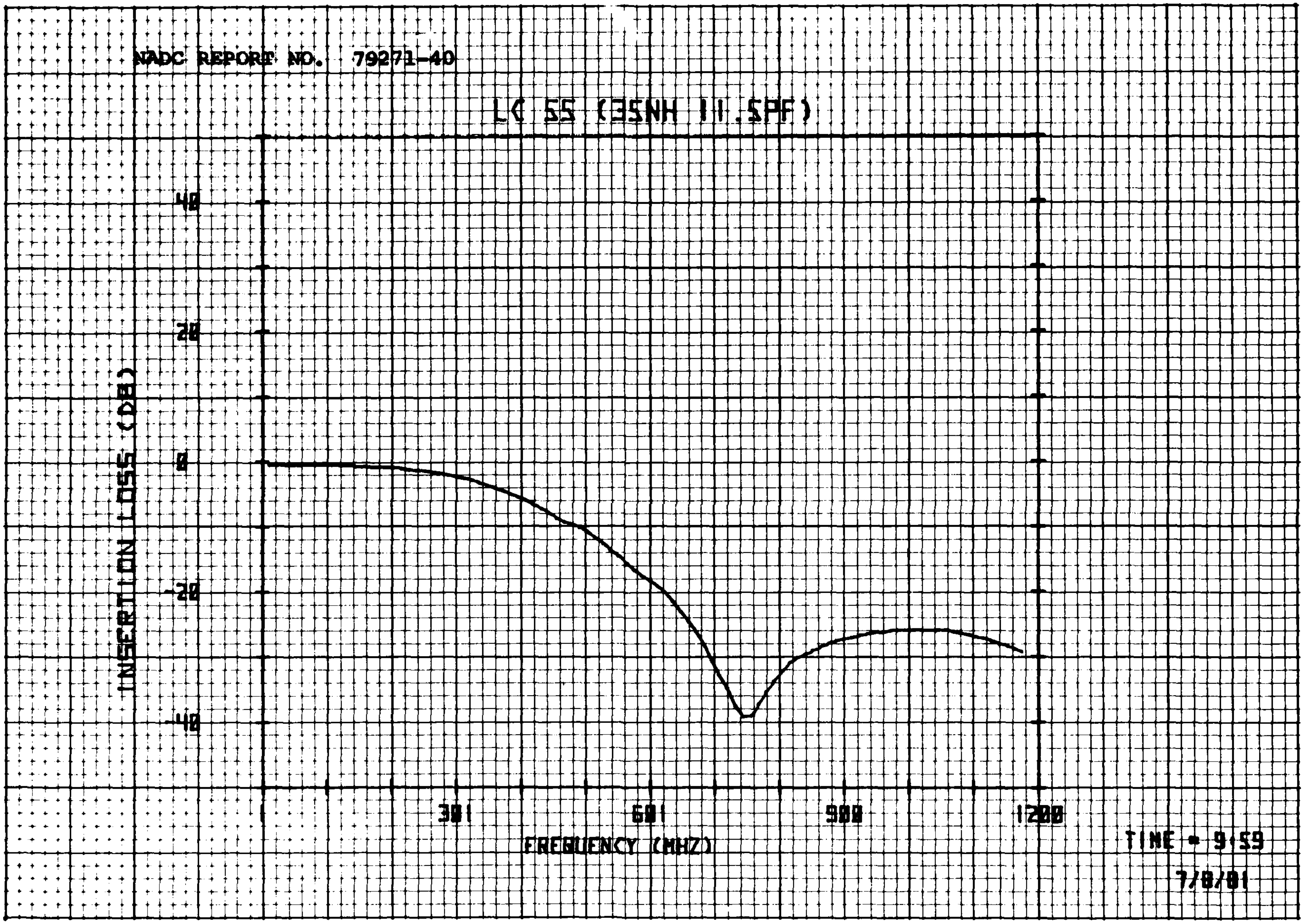

Figure 5.2-4 - Single Section Low-Pass Filter

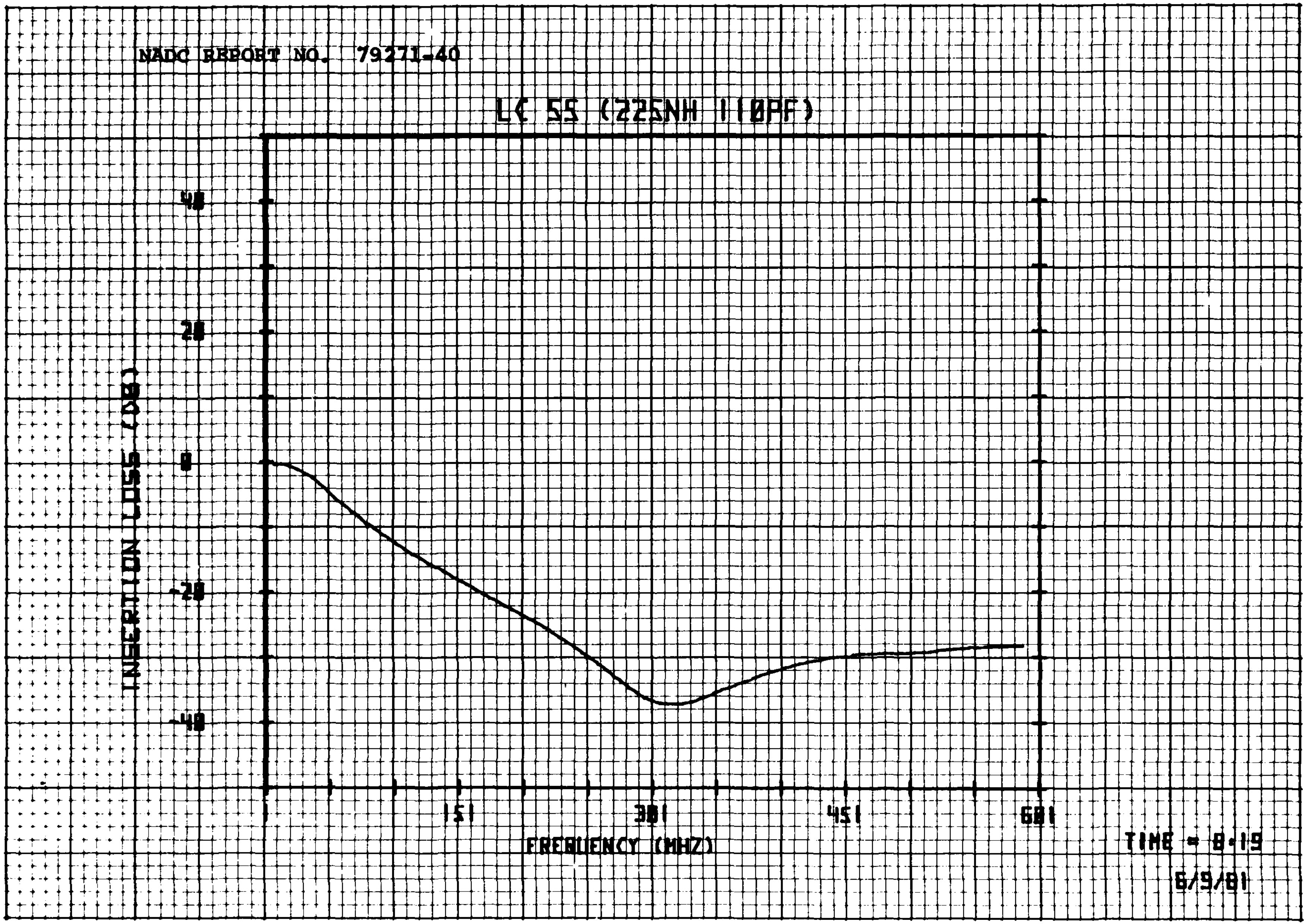

Figure 5.2-5 - Single Section Low-Pass Filter

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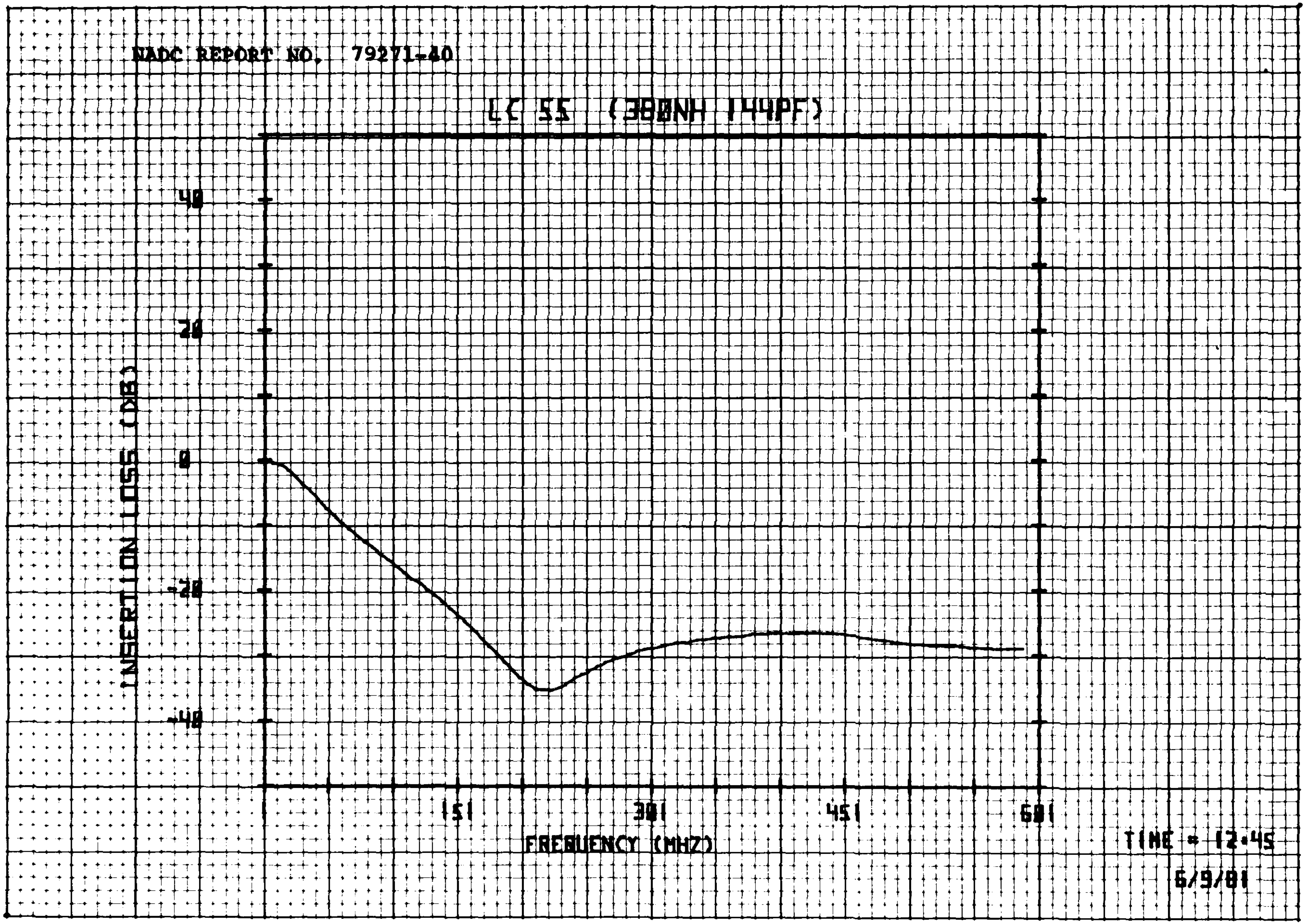

Figure 5.2-6 - Single Section Low-Pass Filter

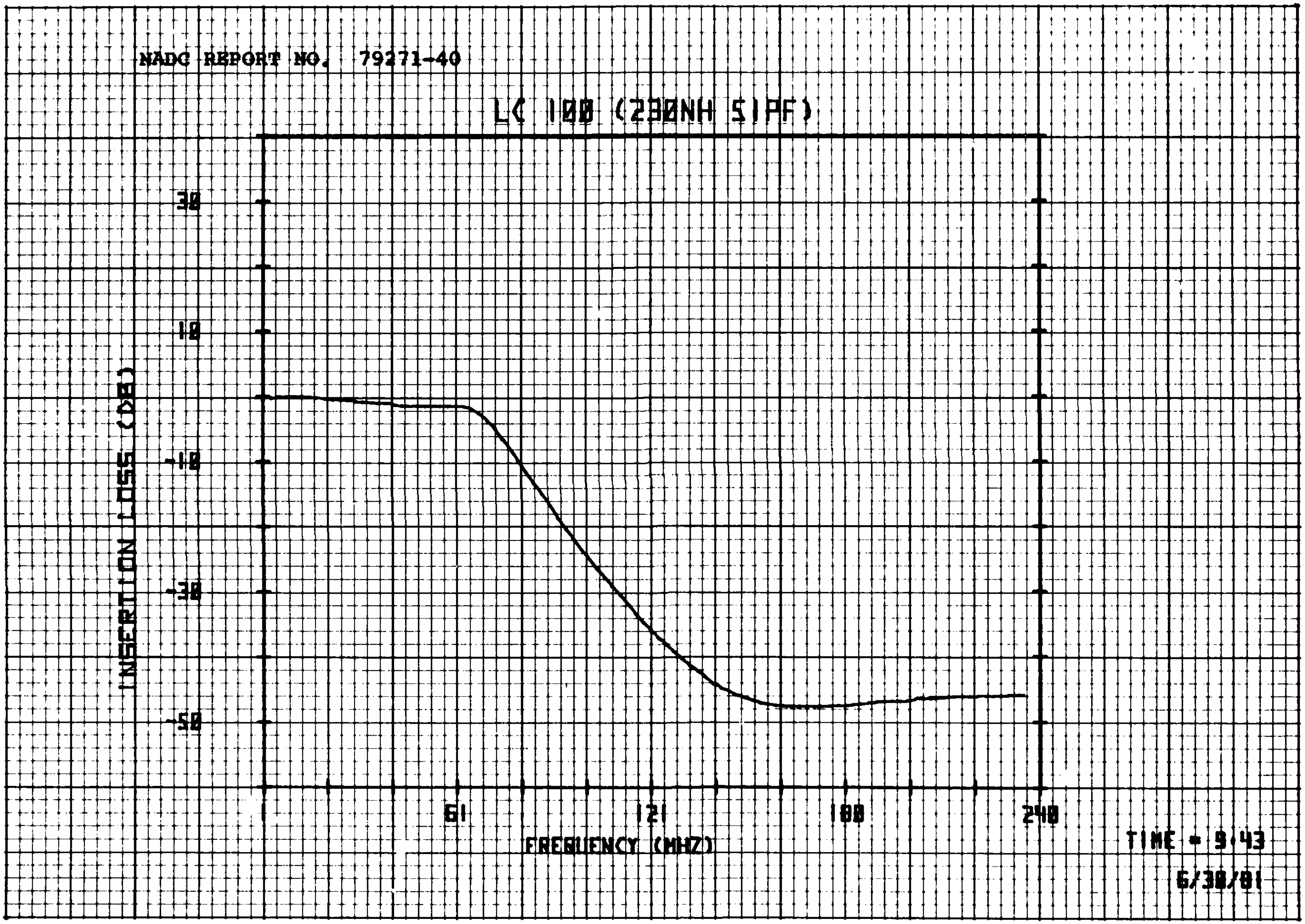

Figure 5.2-7 - Single Section Low-Pass Filter

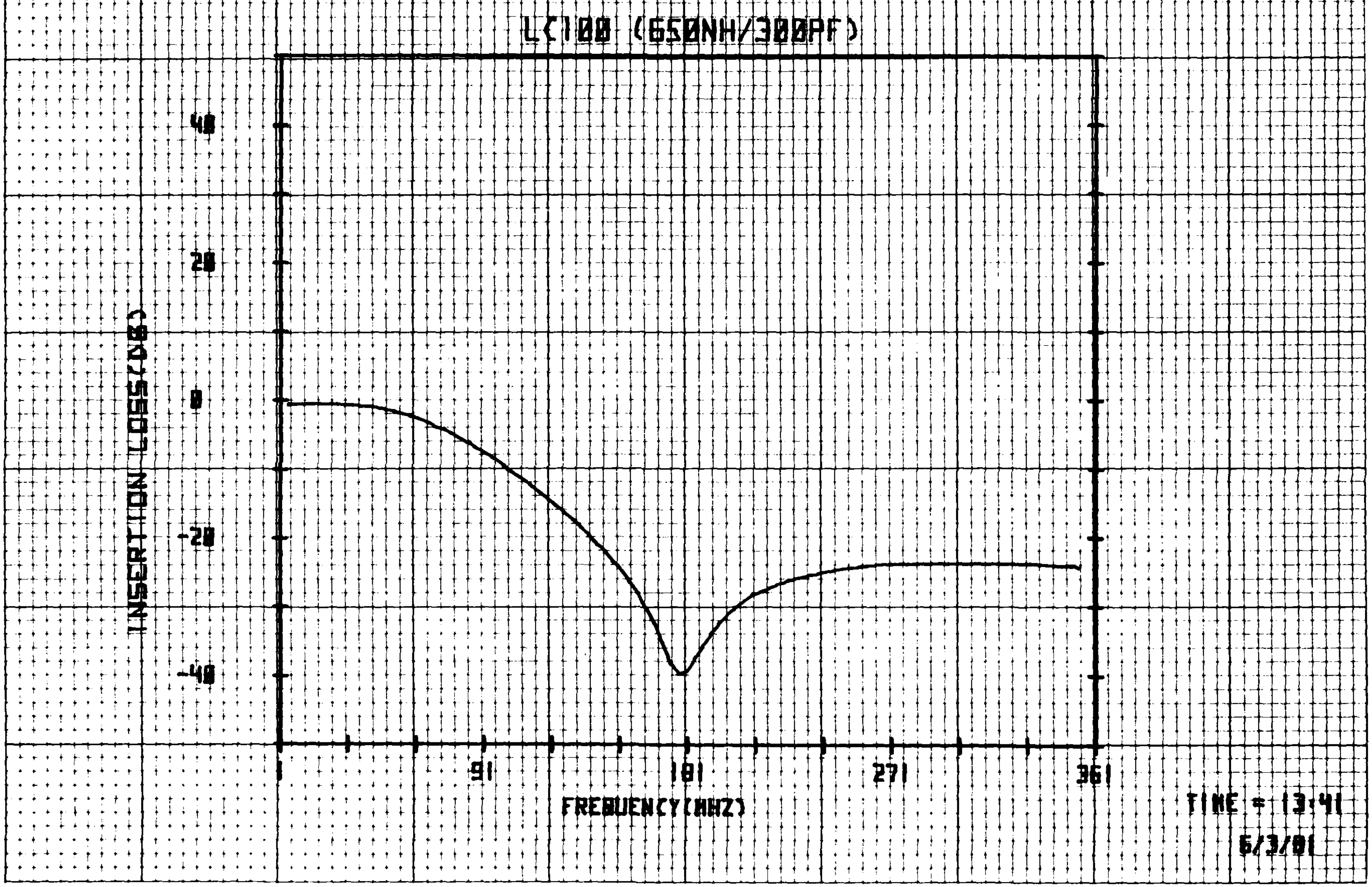

Figure 5.2-8 - Single Section Low-Pass Filter

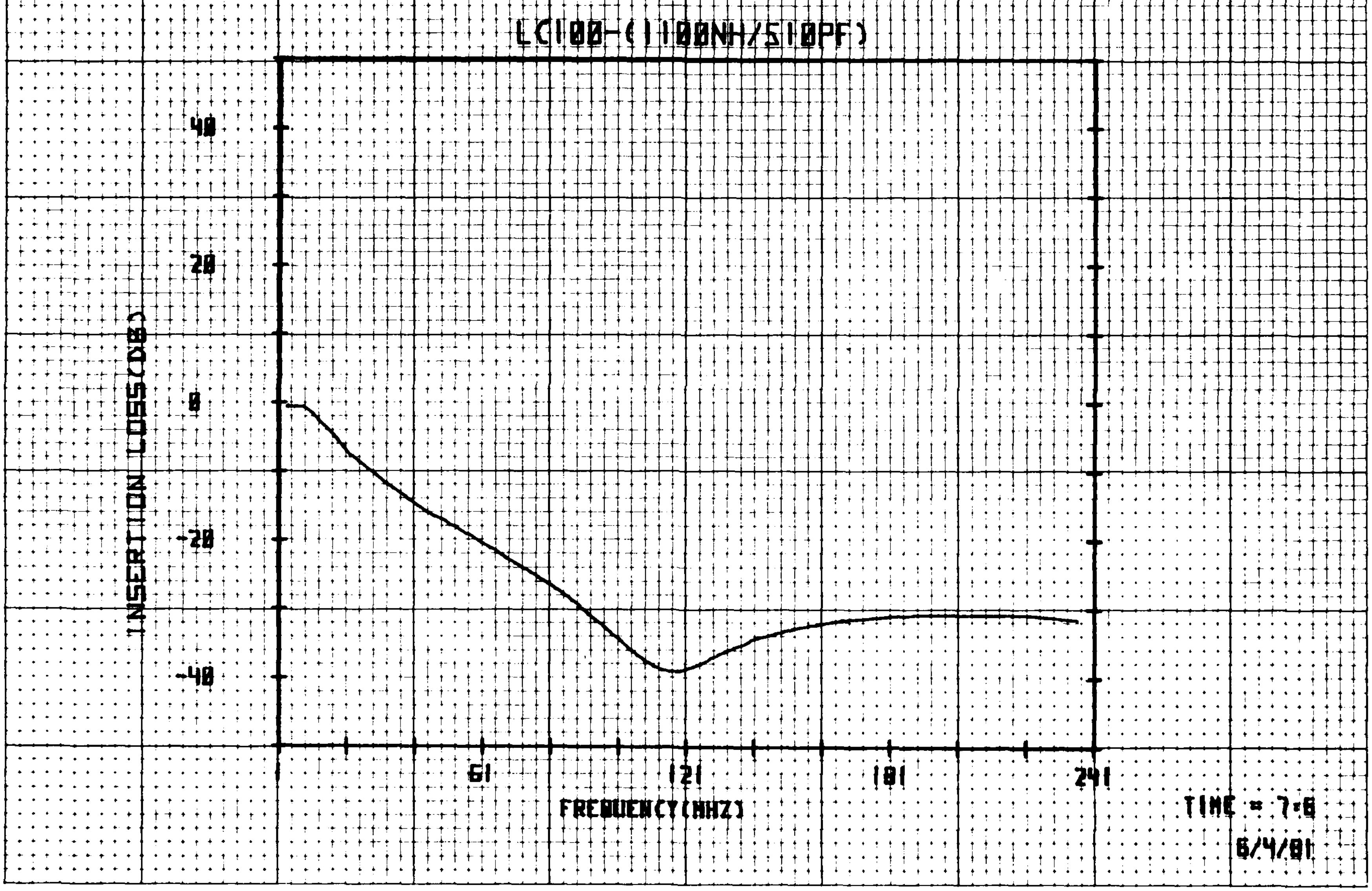

Figure 5.2-9 - Single Section Low-Pass Filter

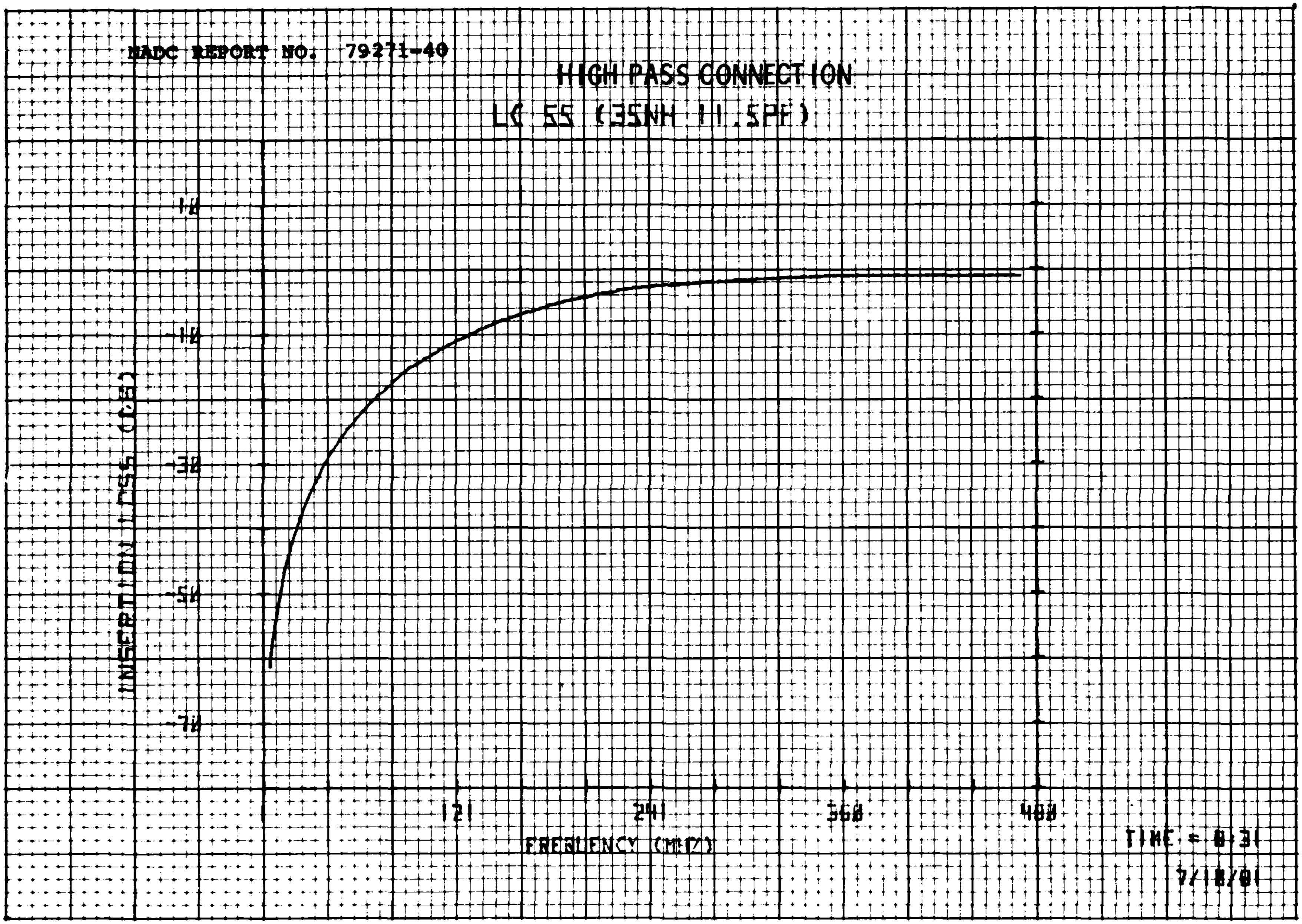

Figure 5.2-10 - Single Section High-Pass Filter

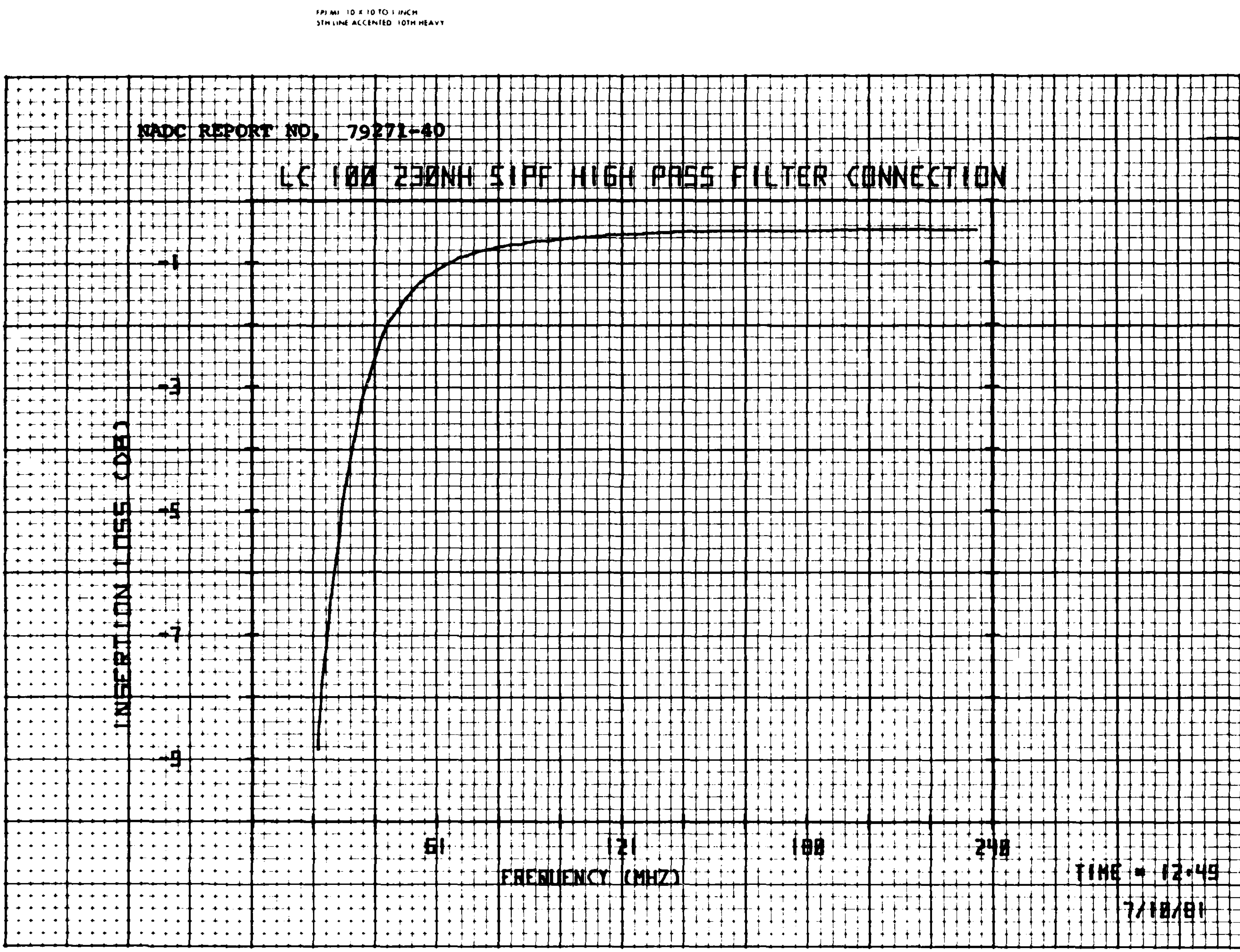

Figure 5.2-11 - Single Section High-Pass Filter

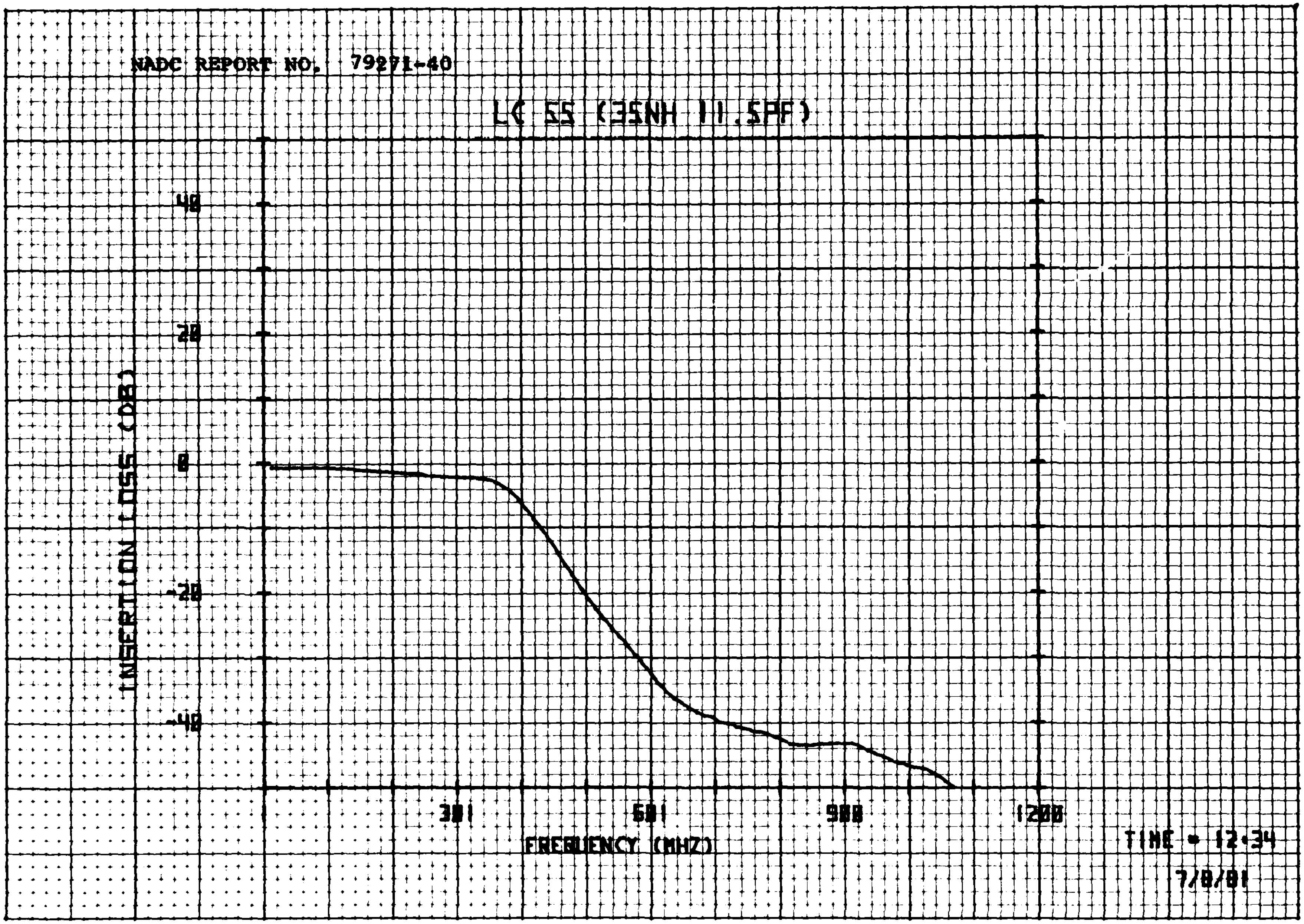

Figure 5.2-12 - Double Section Low-Pass Filter

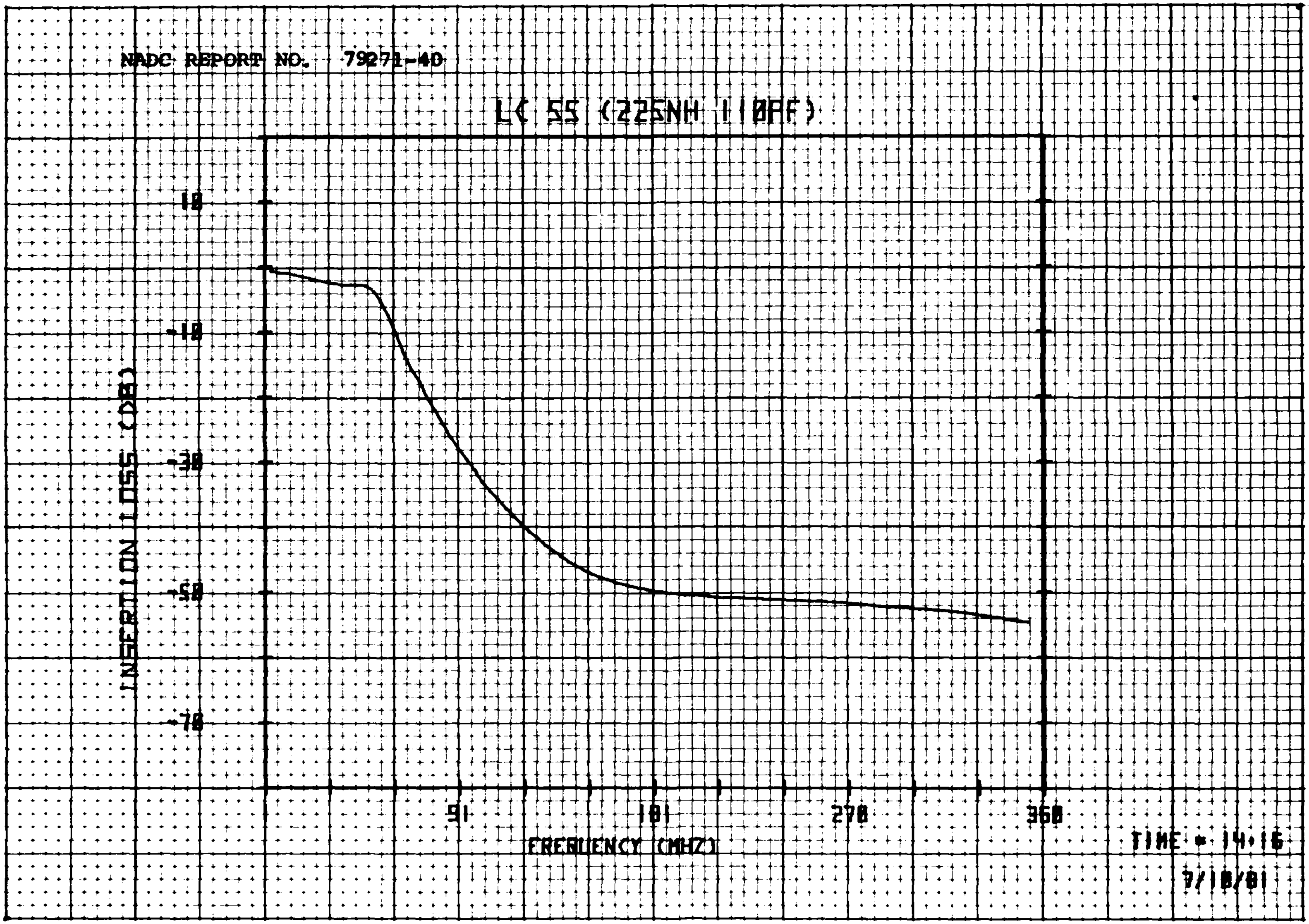

Figure 5.2-13 - Double Section Low-Pass Filter

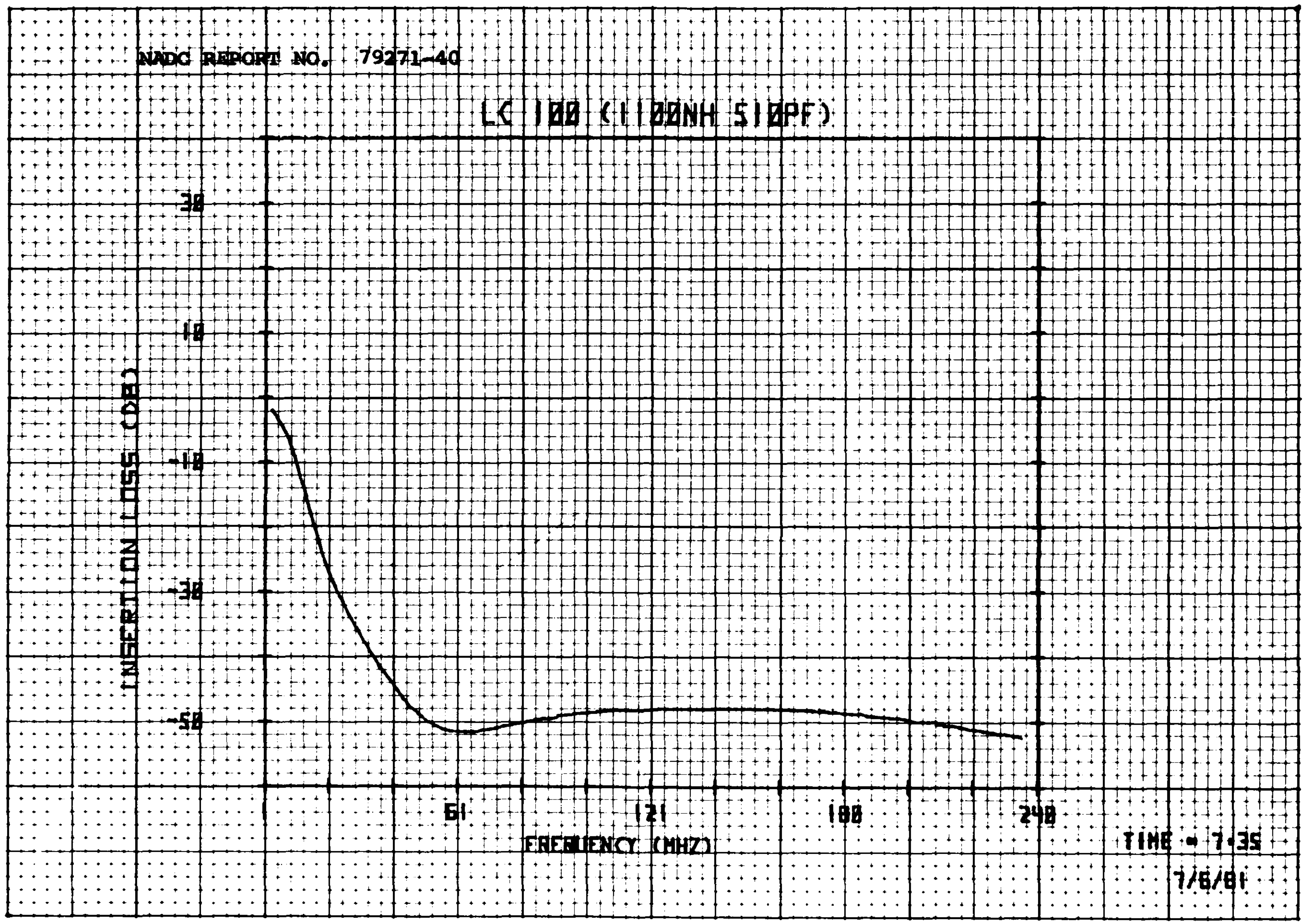

Figure 5.2-14 - Double Section Low-Pass Filter

6.0 CONCLUSIONS

This project has demonstrated the feasibility of producing a monolithic network containing inductors and capacitors and the ability to vary the inductance and capacitance independently. Furthermore, it has been shown that a wide range of inductance and capacitance could be fabricated by using the same set of masks which is a very important factor for producing filters of different cutoff frequencies without using a large number of mask sets.

The bypass filters fabricated can be used as decoupling networks for power supplies. They so function respectably as simple low-pass and high-pass filters. It is felt that the techniques developed in this project have laid the foundation for building full-fledged monolithic filters.

The variation in capacitance should be minimized by investigating other suitable configurations for the electrodes of the capacitor in which the variation in capacitance is less sensitive to mask misalignment. Mechanical means for reducing the amount of misalignment should also be pursued.

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