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13. ABSTRACT (Maximum 200 words)
A single pole evanescent resonator has been designed and built under to test feasibility. The results are shown in Figure 9 and indicate that the filter structure resonates at 3 GHz and has a Q of 460. Due to the lumped element character of the evanescent mode micromachined structure, parasitic resonances do not exist as shown by the measured and theoretically calculated data. As shown by Figure 9, only one resonance from 0 to 20 exists. Higher order periodic resonance are suppressed by the cutoff of the guide and the presence of the post. Using a similar synthesis method, a 2-pole bandpass filter has been designed and simulated at X band. The volume of the designed filter is 10.5 mm^3 compared to a 400 mm^3 2-pole micromachined resonant cavity filter with comparable performance. To add extra poles to an evanescent filter, additional posts separated by evanescent cavities are needed. This makes multiple pole filters easy to fabricate since only two silicon wafers are needed to create the cavity. The capability to fabricate these filters using IC fabrication techniques [5,6] allows for unique designs that may reduce size even further.

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FINAL REPORT

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EVANESCENT MODE FILTERS

By

LINDA P.B. KATEHI

The University of Michigan
Ann Arbor

Hand delivered
by B. Webster...

February 2001

PROJECT DESCRIPTION

A. INTRODUCTION

Typical communication satellites, Figure 1, employ traditional waveguide-base front-end architectures due to excellent electrical performance and high reliability. However, these systems are extremely massive and utilize large volume mostly attributed to the low-insertion loss waveguide switch, diplexer and waveguide-packaged solid-state power amplifier. These three components are interconnected by waveguide sections for compatibility and result in subsystems with dimensions of 18cm x 40.6 cm x10.5 cm as shown on Figure 2. Despite the large volume and mass, metallic waveguide has been the transmission medium of choice in space applications due to the low-loss requirements. Its use in communication systems has resulted in overall system loss of less than 2 dBs. Replacement of the waveguide components by micromachined ones without substantially affecting electrical performance can lead to a breakthrough in wireless communications [1], [2]. Communications via satellites require optimum high frequency performance, lightweight hardware, advanced packaging, high-density interconnect technology and high reliability. The use of electronics in space poses interesting but grand challenges. It also provides the opportunity for using revolutionary concepts in circuit design, fabrication and implementation to achieve what is considered by today's standards as ultimate performance, minimal volume and very low cost. Circuit optimization methods applied to existing technologies cannot meet the specifications, but critical advancements based on new concepts at fundamental levels of circuit design and diagnostics are needed. The capability to integrate the RF system on a single chip while preserving electrical performance will provide a breakthrough in communications systems for any type of wireless applications. The objectives of this effort is to attempt a revolutionary filter/diplexer design by combining on-wafer integration and packaging along with micromachined waveguide-like structures into a single monolithic arrangement that exhibits very high Q and very small size. In addition, this monolithic filter/diplexer will have the ability to electronically achieve reconfigurable performance using MEMS devices. Such a device will provide desired RF filtering in addition to frequency hopping and can be used in filter banks due to very small size. While not as small as microelectrical mechanical filters [4], the proposed filter devices will have a size of the order of a few millimeters for operation in the low end of the microwave spectrum. This size is considerably smaller than that of any other conventional filter

Satellite RF Front End on a Chip

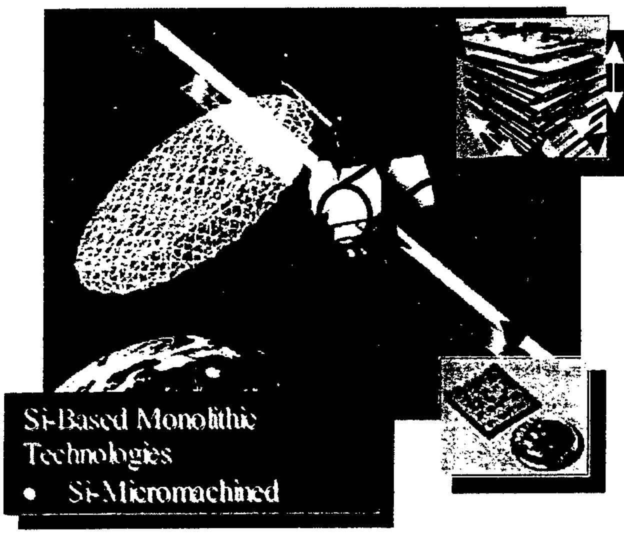


Figure 1: Waveguide-Based Satellite RF Front End

of similar performance. Furthermore these filters can be integrated monolithically with the conventional planar technology while they provide the smallest possible size along with excellent performance for frequency ranges above 1-2 GHz. The filters proposed herein are equivalent to lumped element filters where the lumped L and C is provided by appropriate use of micromachined shapes. This is the underlining concept that leads to drastic reduction of size. To accomplish this goal advanced electronics material technology and high-density fabrication techniques along with electromagnetic analysis tools will be used. The development of such a diplexer will demonstrate a key concept in advanced communications architectures and systems and it will have a major impact on wireless technologies.

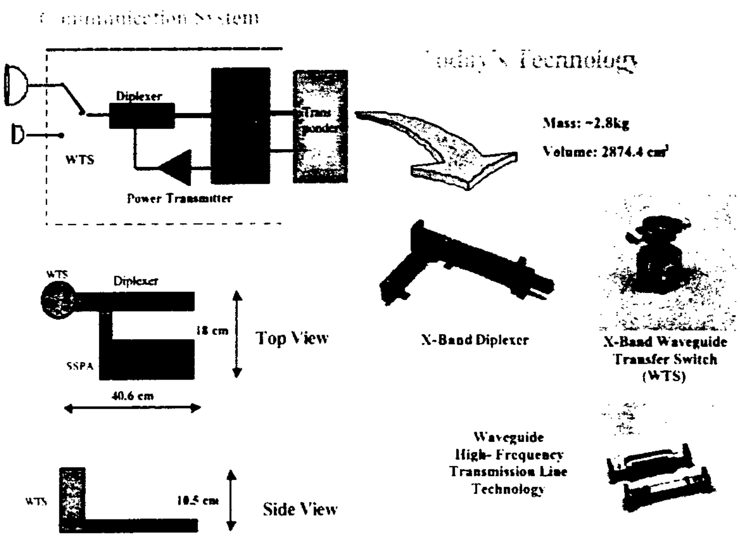


Figure 2: Conventional Waveguide RF Front-End

B. SUMMARY OF PERFORMED STUDY

The design of a diplexer reduces to a filter design with two very narrow com-munication frequency channels highly isolated. The study performed during the past few years at Michigan has demonstrated the following [1-6]:

- In monolithic filter de-signs high-Q performance can only be achieved by use of filters that include either resonating elements printed on membranes or micro-machined waveguide reson-ant cavities (Figure 3).
- The use of membrane filters is limited to high frequencies due to the size of the resulting filter and because the achieved Q cannot exceed 500 [1,2].
- Si micromachined resonator cavity filters can be integrated monolithically and can provide filters with drastically reduced height (1-1.5mm). However, the use of resonating cavities limits the transverse size of the filter to a minimum of half free-space wavelengths (about 1.5mm in W band, 1.5cm in X band and 5 cm in L Band) [3].
- The need to acquire high Q and small size for frequencies in the low end of the microwave spectrum, requires the use of non-resonant monolithically integrated structures.
- Small size and high Q may require frequency and input match adjustments. Such adjustments, while necessary in the case of very high-Q filters, are impossible without the use of MEMS.
- The ability to electronically adjust frequency and bandwidth will provide additional filter functionality such as tunability, switching and frequency hopping that will lead to new architectures in communication systems.

Based on the above observations we concluded that small size, high-Q filters or filter banks with high isolation between the adjacent channels can be achieved by use of micromachined evanescent-mode cavities that appropriately couple to each other and to the input/output microstrip or coplanar waveguide transmission lines. The use of evanescent mode structures provides small size and the ability to tune via small variations in some geometrical parameters using MEMS structures. Studies performed at Michigan under ARO/DARPA funding have demonstrated the potential of this filter technology to provide excellent performance and very small size. While, high isolation between the adjacent channels is intrinsic to this filter design, further improvements can be achieved by use of the on-wafer packaging techniques, which have demonstrated the ability to provide isolation as high as -80dB to -100 dB [4-6].

The performed study focused on the development of evanescent mode resonators and filters using micromachined cavities in S, L and X Bands. A detailed description of the effort in each one of these two steps is given below.

Evanescent-mode Micromachined Filters

Historically, the development of microwave passive networks consists mainly of finding distributed components which can provide inductive and capacitive reactances to replace the lumped elements employed by the filter prototype. Although distributed constant networks are necessary for high-Q reactance elements, it is not essential that these networks be based on structures of the conventional transmission line type. For some years now literature has been accumulating on network designs using waveguide sections below their cut-off frequency [17,18]. Lebedev and Guttsait [18] first discovered that resonant behavior can be achieved by any evanescent mode if appropriate terminating conditions (a conjugate reactance) for that mode are provided.

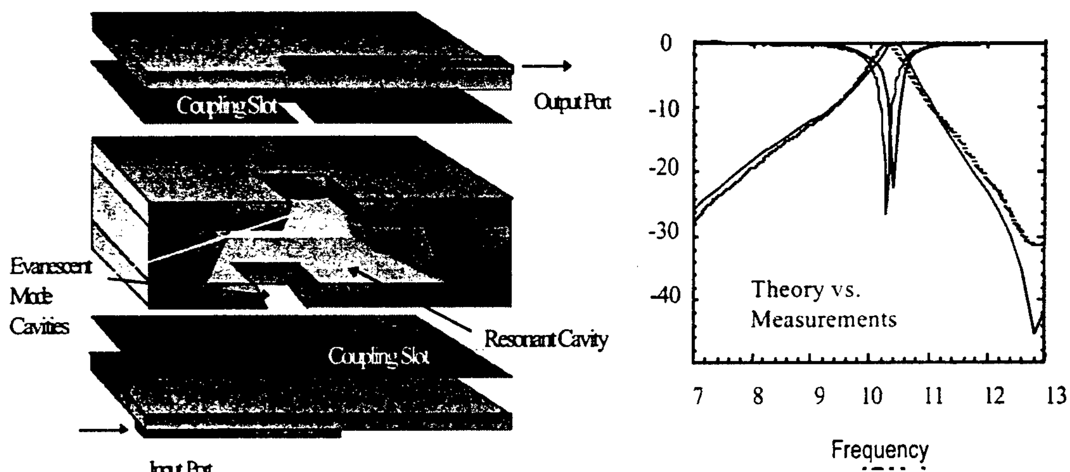
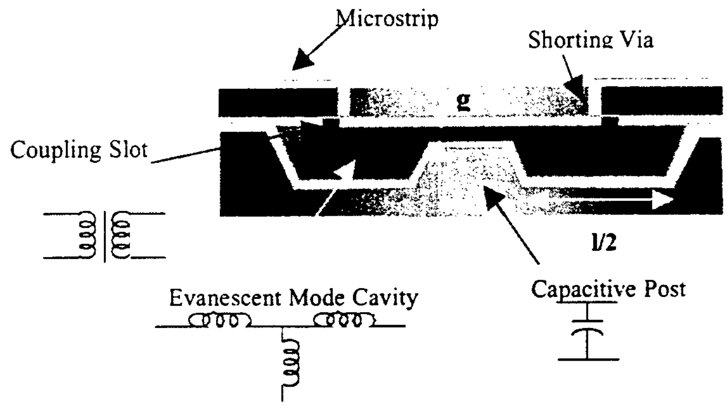
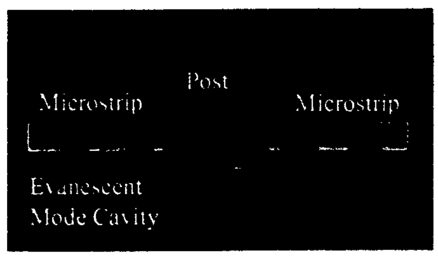


Figure 4: Single-Pole Micromachined Filter with Evanescent and Resonant Cavities. Theoretically Calculated Q=569, Measured Q=530. Insertion Loss at Center Frequency IL=-.3dB, BW=5%.

Any band-pass filter can be realized from a low-pass prototype by appropriate frequency and impedance scaling. The band-pass prototype can then be converted to a lumped element configuration where shunt LC resonators are connected through admittance inverters. It can be proven that this circuit can reduce into a sequence of evanescent waveguide sections appropriately connected by negative (capacitive) coupling. This negative coupling can be provided by resonating cavities as shown in Figure 4 [17] or by capacitive obstacles as shown in Figure 5. Preliminary results have demonstrated the ability to provide very high Q using resonant cavities (see Figure 6). While this approach results in filters that compare to waveguide ones in terms of performance requirements, the size of the resonating cavities may prohibit operation at lower frequencies. Specifically for a 5%, X-band single pole filter, the size of the resonating cavity is 15mm (width) x 20mm (length) x 0.5mm (height). The same filter scaled to 2.5 GHz would require a length of 8 cm and a width of 6 cm.



Magnetic Field Patterns of an Evanescent Mode



H-Field Distribution in the Evanescent Mode Sect

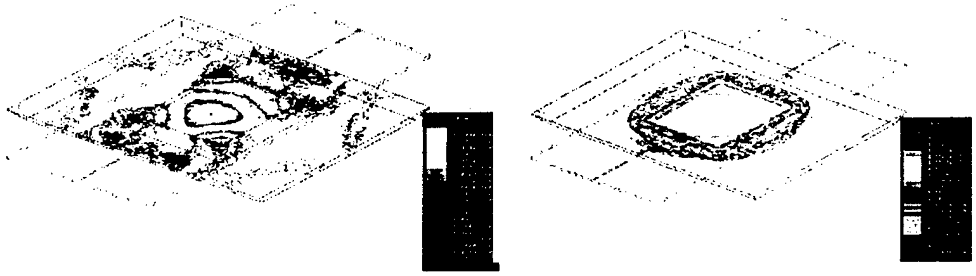


Figure 6:Single Pole Evanescent Mode Filter

When size becomes an issue, the evanescent mode filter of Figure 5 is an appropriate solution where by use of capacitive obstacles such as the pyramidal posts, shown in the figure, required filter size is reduced considerably. As part of this effort we will demonstrate the use of this approach in the development of S- and X- band tunable filters and we will evaluate the effectiveness of the design in terms of size, Q, bandwidth and loss.

The lumped element equivalent to the inductive section (evanescent mode section) of guide is that of a transmission line with imaginary impedance and leads to the development of effective lumped element models. For a single pole evanescent mode filter the lumped element models are shown in Figures 6 and 7. Empirical formulas for the capacitance and inductance of the variable height post have been developed using quasi-static techniques and have been verified by a high-frequency simulator, Ansoft's HFSS. These formulas can be utilized to design an evanescent

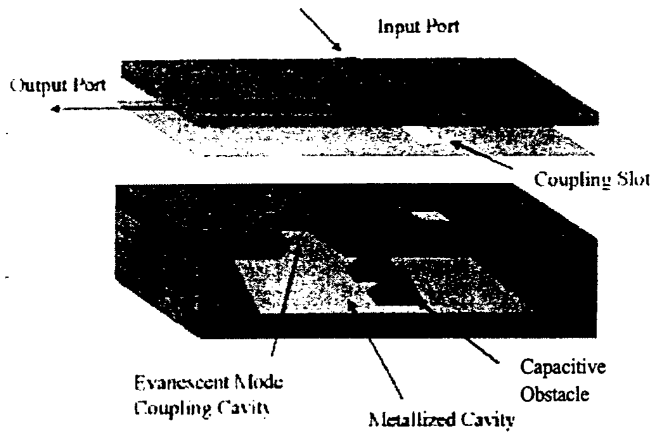
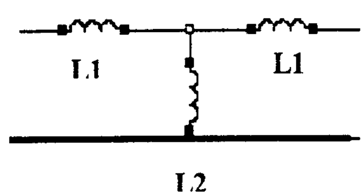


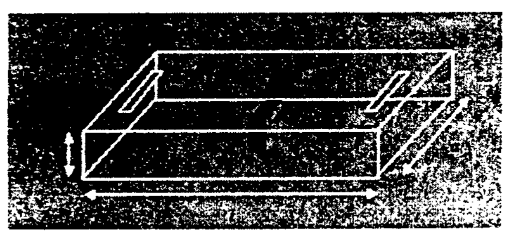
Figure 5: Evanescent Mode Filter with Capacitive Posts

multi-pole filter from the standard low-pass designs. In addition, from these simple formulas trends may be developed to predict changes in filter response, center frequency and bandwidth, by inducing small changes in dimensions, as shown in Figure 8. Understanding these trends is very important to electronic tuning via use of MEMS devices

A single pole evanescent resonator has been designed and built under to test feasibility. The results are shown in Figure 9 and indicate that the filter structure resonates at 3 GHz and has a Q of 460. Due to the lumped element character of the evanescent mode micromachined structure, parasitic resonances do not exist as shown by the measured and theoretically calculated data. As shown by Figure 9, only one resonance from 0 to 20 exists. Higher order periodic resonance are suppressed by the cutoff of the guide and the presence of the post. Using a similar synthesis method, a 2-pole bandpass filter has been designed and simulated at X band. The volume of the designed the filter is 10.5 mm^3 compared to a 400 mm^3 2-pole micromachined resonant cavity filter with comparable performance. To add extra poles to an evanescent filter, additional posts separated by evanescent cavities are need. This makes multiple pole filters easy to fabricate since only two silicon wafers are needed to create the cavity. The capability to fabricate these filters using IC fabrication techniques [5,6] allows for unique designs

Model of an Evanescent Section and of Capacitive Post





$$L_2 = \frac{Zcavity}{w \cdot Sinh[\gamma_e \cdot \frac{l}{2}]}$$

w=Radial Frequency
λ=Free Space Wavelength
λ_c=Cutoff Wavelength of The Guide
k=Wavenumber
η=Free Space Impedance (120π
K=Proportionality Constant

$$L_1 = \frac{Zcavity \cdot Tanh[\gamma_e \cdot \frac{l}{2}]}{w}$$

$$Zcavity = \eta \cdot \frac{b}{a} \cdot \frac{1}{\sqrt{(\frac{\lambda}{\lambda_c})^2 - 1}}$$

$$C_{post} = \frac{K \cdot \epsilon' \cdot [(Wa)^{\cdot\cdot} \cdot (Wx)^{\cdot\cdot}]}{(1-g)}$$

$$\gamma_e = k \cdot \sqrt{(\frac{\lambda}{\lambda_c})^2 - 1}$$

Figure 7: Empirical Formulas for Evanescent Mode Sections where Wa and Wx is the Width and Length of the Capacitive Post

that may reduce size even further.

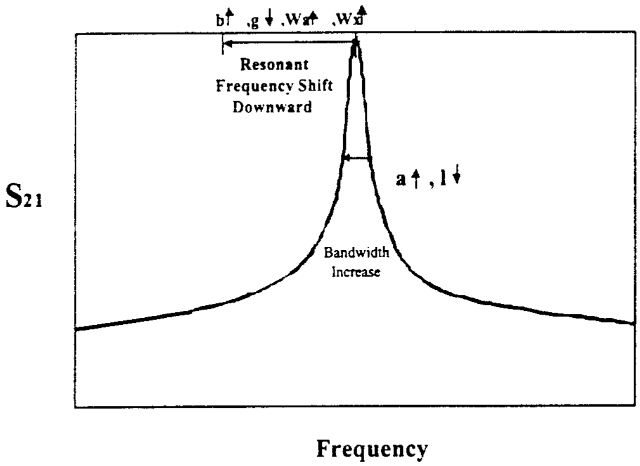


Figure 8: Trends in Filter Performance Based on Varying Geomertrical Parameters

Figure 10 indicates two possible designs for a multipole evanescent mode filter. Specifically, Figure 10a shows a three-pole evanescent mode filter with the input and output lines in a perpendicular orientation to further reduce size. The second design (Figure 10b) illustrates a possible arrangement for a diplexer with high isolation between the two output ports. This diplexer is made out of two cavities stacked vertically and coupled through a slot that has a gamma shape designed to control the coupling. This configuration is expected to have very high isolation between the two output ports due to the high out-of-band isolation in each filter and the relative position between the two cavities.

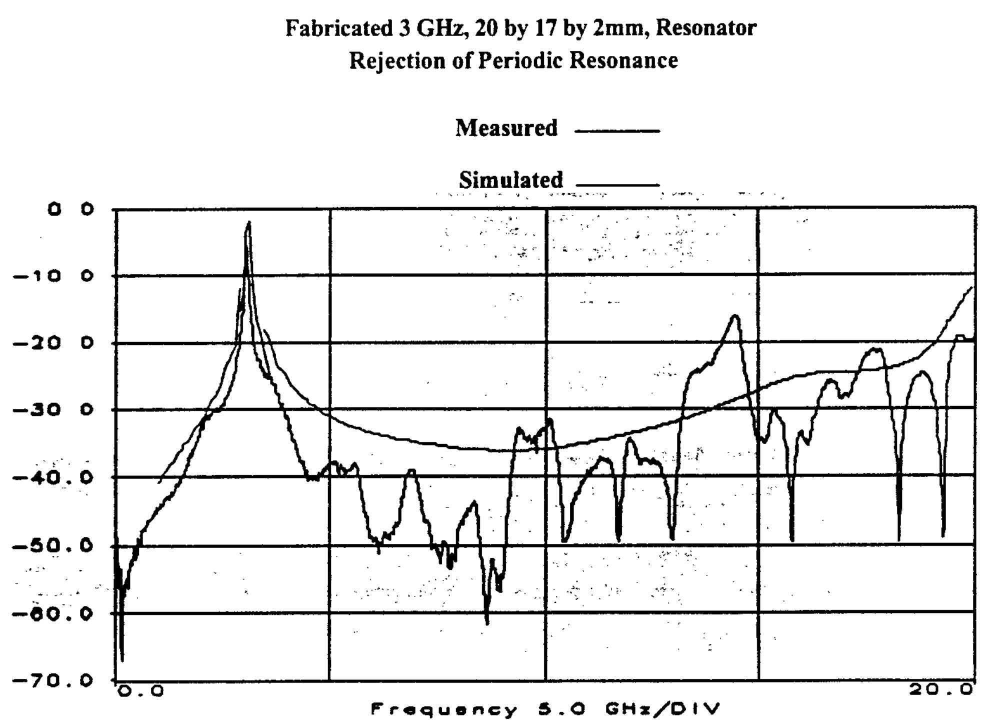


Figure 9: Measurements vs. Theory for a Single Pole Filter

While some very fast initial successes have been achieved, the full potential of the approach has not been explored. This further study is presently underway (funded by NSF) to understand the impact of tuning on the evanescent modes and their implication to filter design. Furthermore, in addition to Si, the evanescent cavities are developed using a variety of materials including electromagnetic bandgaps.

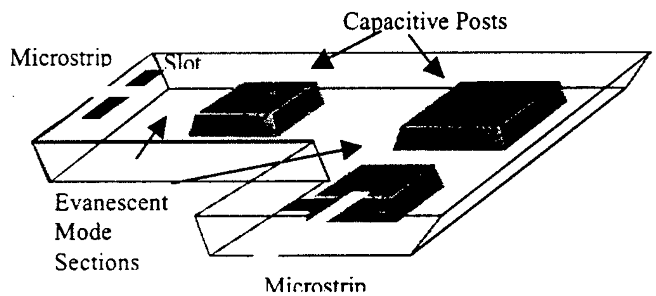


Figure 10a: Three-Pole Evanescent Mode Filter

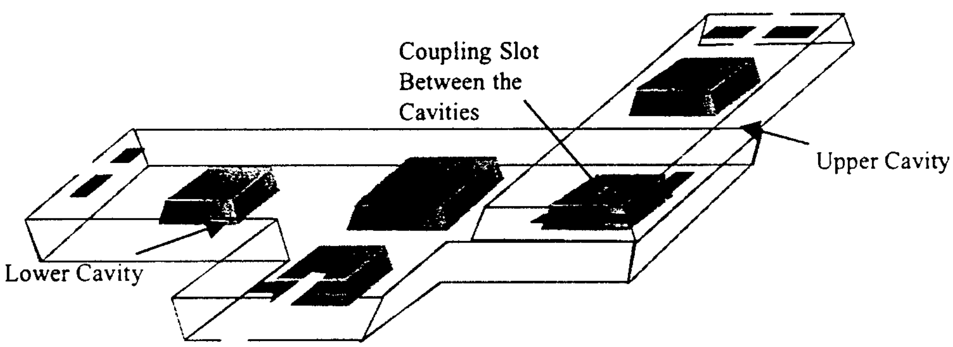


Figure 10b: Diplexer Design with Multiple Cavities Including Evanescent Mode Sections and Capacitive Posts.

REFERENCES CITED

1. L.P.B. Katehi et.al., ***Si Micromachining in High-Frequency Applications***, *CRC Handbook on Si Micromachining*, 1995.
2. L. P. B. Katehi, ***Novel Transmission Lines for the Submillimeter-Wave Region***, *IEEE Proceedings*, Vol. 80, No. 11, November 1992, pp. 1771-1787.
3. J. Papapolymerou, Jui-Ching Cheng, J. East and L.P.B. Katehi, ***A Micromachined High-Q, X-Band Resonator***, Microwave and Guided Wave Letters, Vol. 7, No. 6, pp. 168-170, June 1977.

4. R. F. Drayton, and L. P. B. Katehi, ***Development of Self-Packaged High Frequency Circuits Using Micromachining Techniques***, *IEEE Trans. on Microwave Theory and Techniques*, Vol. 43, No. 9, Sept. 1995.

5. R. F. Drayton, R. M. Henderson, and L. P. B. Katehi, ***High Frequency Circuit Components on Micromachined Variable Thickness Substrates***, *IEE Electronic Letters*, Vol. 33, No. 4, February 13th, 1997.

6. R. F. Drayton, Rashaunda M. Henderson and Linda P.B. Katehi, ***Monolithic Packaging Concepts for High Isolation in Circuits and Antennas***, in press in the IEEE Trans. on Microwave Theory and Techniques, Vol. 46, No. 7, pp. 900-906, July 1998.

7. Clark Ngyuen, Linda P.B. Katehi, and Gabriel Rebeiz, ***Micromachined Devices for Wireless Communications***, IEEE Proceedings, Vol. 86, No. 8, August 1998.

8. George Ponchak and Linda P.B. Katehi, ***Measured Attenuation of Coplanar Waveguide on CMOS Grade Silicon Substrates with a Polyimide Interface Layer***, Electronic Letters, Vol. 34, No. 13, pp. 1327-1329, June 1998.

9. Katherine J. Herrick. Tom Schwarz and Linda P.B. Katehi, ***Si-Micromachined Coplanar Waveguides for Use in High Frequency Circuits***, IEEE Transactions on Microwave Theory and Techniques, Special Issue on Millimeter-Wave Technologies, Vol. 46, No. 6, June1998, pp. 762-768

10. K. E. Petersen, ***Micromechanical Membrane Switches on Silicon***, *IBM J. Res. Develop.*, vol. 23, no. 4, pp. 376-385, July 1971.

11. L. E. Larson, R. H. Hackett, M. A. Melendes, and R. F. Lohr, ***Micromachined Microwave Actuator (MIMAC) Technology - A New Tuning Approach for Microwave Integrated Circuits***, *IEEE Microwave and Millimeter-Wave Monolithic Circuit Symposium*, pp. 27-30, 1991.

12. J. J. Yao and M. F. Chang, ***A Surface Micromachined Miniature Switch for Telecommunications Applications with Signal Frequencies From DC up to 4 GHz***, *The 8th International Conference on Solid-State Sensors and Actuators and Eurosensors IX*, pp. 384-387, 1995.

13. C. Goldsmith, J. Randall, S. Eshelman, and T. H. Lin, ***Characteristics of Micromachined Switches at Microwave Frequencies***, *IEEE MTT-S Digest*, pp. 1141-1144, 1996.

14. Sergio Pacheco, Clark T. Nguyen, and Linda P.B. Katehi, ***Micromechanical Electrostatic K-Band Switches***, 1998 International Symposium in Microwave Theory and Techniques Society.

15. F. Brauchler, S. Robertson, J. East, and L. P. B. Katehi, ***W-Band Finite Ground Coplanar (FGC) Line Circuit Elements***, *IEEE MTT-S Digest*, pp. 1845-1848, 1996.

16. M.I Herman, K.A Lee E.A Kolawa, L.E. Lowry and A.N. Tulintseff, "***Novel Techniques for Millimeter-Wave Packages***, *IEEE Transactions on Microwave Theory and Techniques*, MTT-40, No. 1, pp. 81-88, January 1992.

17. George F. Craven and C.K. Mok, ***The Design of Evanescent Mode Waveguide Bandpass Filters for a Prescribed Insertion Loss Characteristic***, *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-19, No. 3, March 1971.

18. I.V. Lebedev and E.M. Guttsait, ***Resonator of the Subcritical Waveguide Type***, *Radiotekh. Elecktron*, Oct. 1956, pp. 1303.

University of Michigan
College of Engineering
Department Chairs Meeting

Tuesday, February 20, 2001
3:15-5:00 PM
2210 LEC

Agenda

1. FY2001 Mid-Year Financial Reports for COE Academic Departments (Mary Kurta)
2. Preliminary Financial Planning for FY2002 and Schedule for Budget/Merit Processes (Judith Pitney)
3. Supplemental Funds for Instruction (Linda Katehi)
4. Status Update of Promotion/Tenure Process (Linda Katehi)
5. Environment – Update on MIT Conference (Linda Katehi)
6. Excellence in Staff Service Awards Nominations (Steve Director)
7. Nominations for National Awards (Steve Director)

02/19/01

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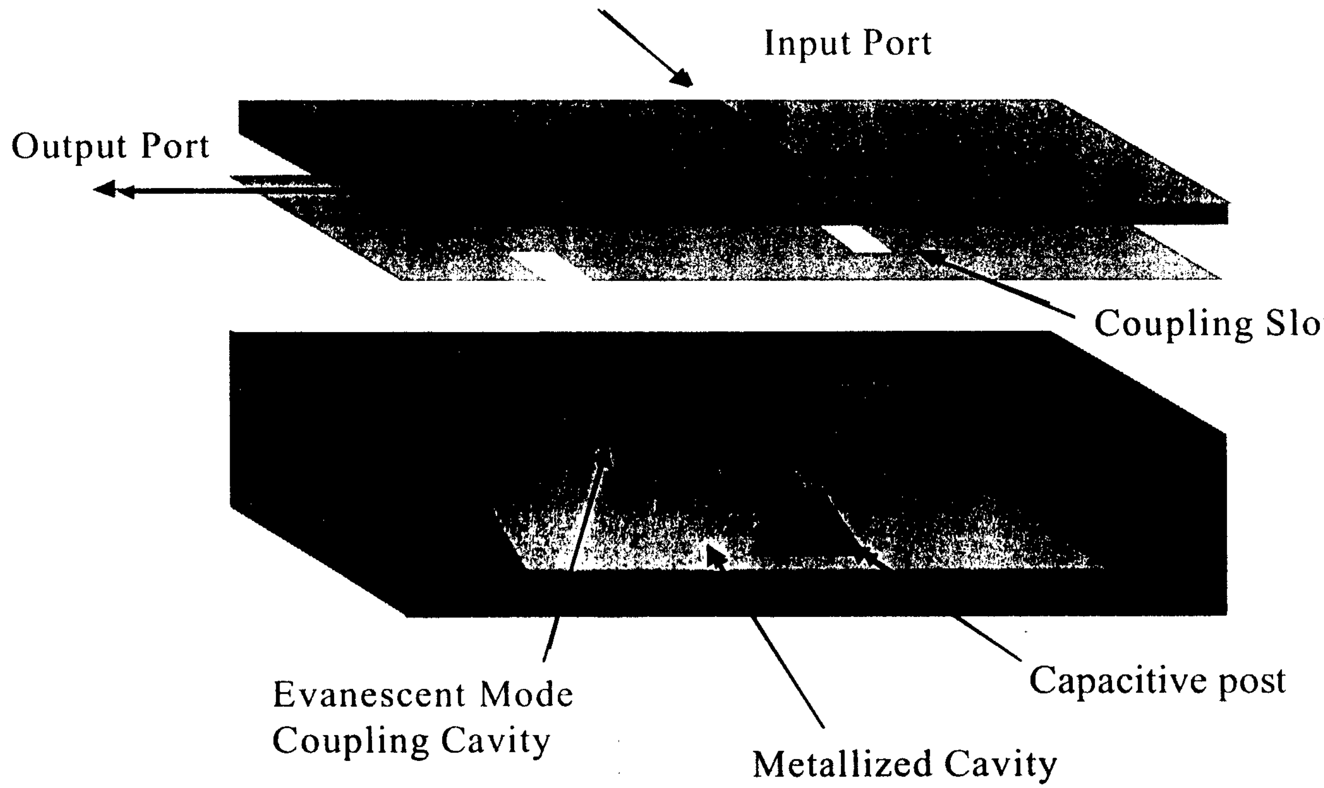
Mode Resonators

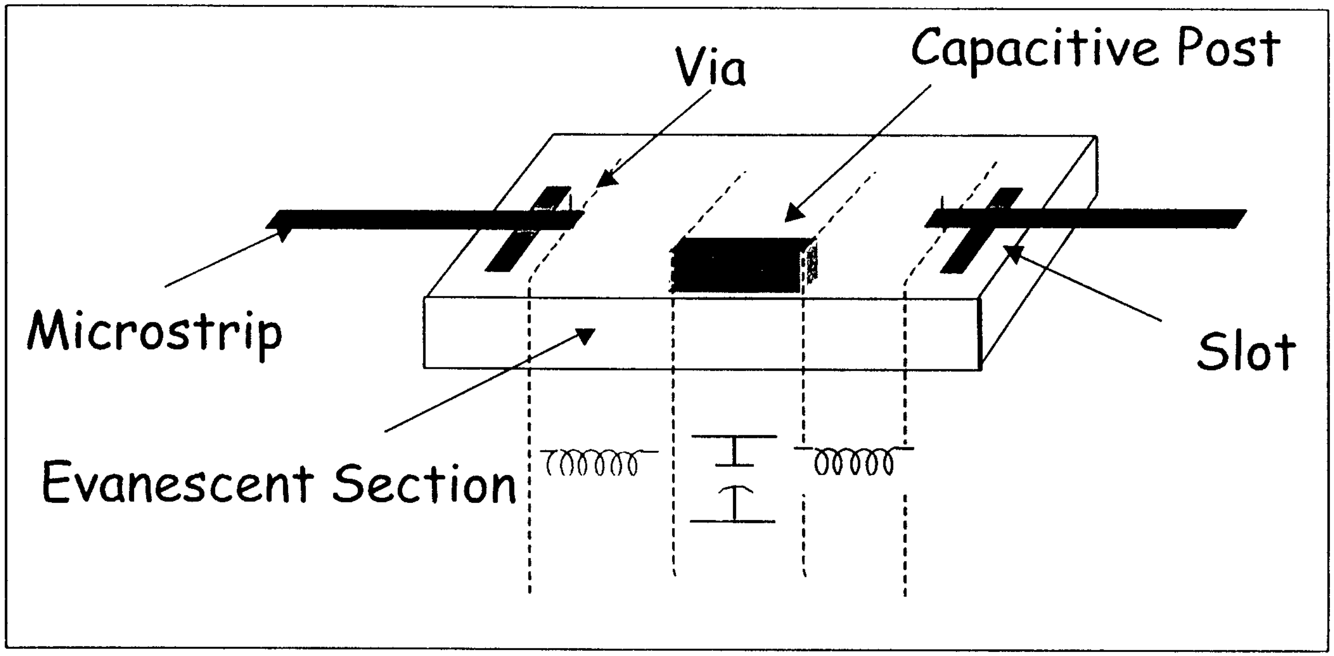
Thomas A. Sch[illegible] Linda P.B. Katehi
University of Michigan Radiation Lab

Darpa Contract No DAAG5[illegible]

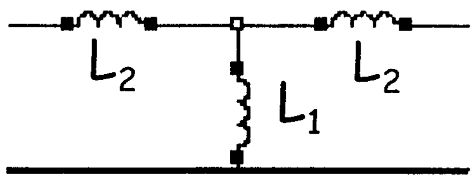
- Investigate Possible Architectures
- Identify Trade-Offs
- Develop Designs
- Fabricate and Measure to Verify

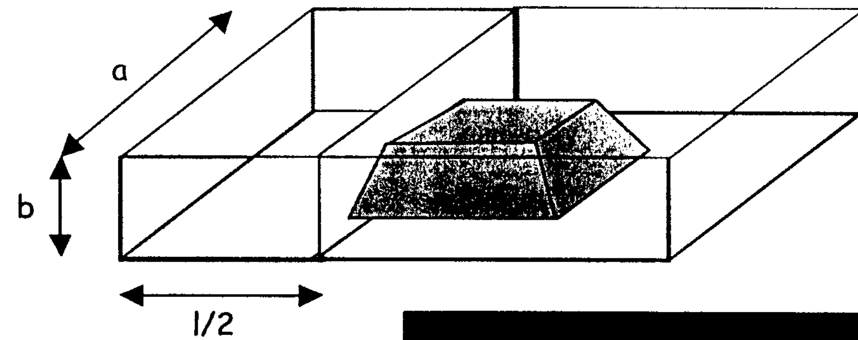
University of Michigan




Via
Capacitive Post
Microstrip
Slot
Evanescent Section

University of Michigan





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k=Wavenumber
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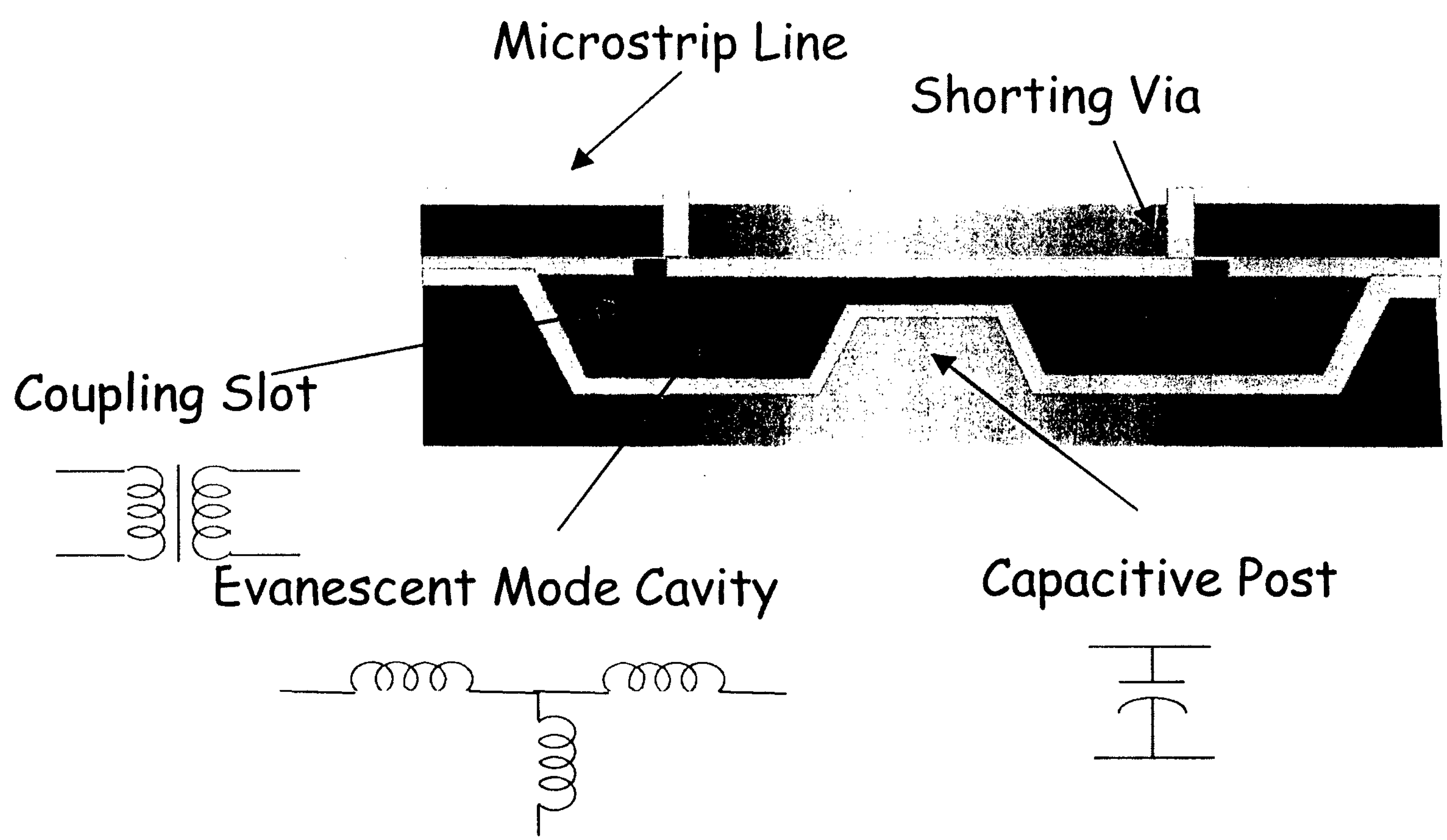
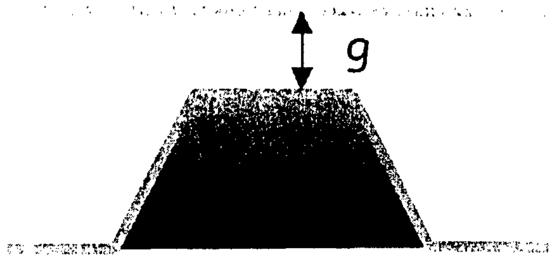
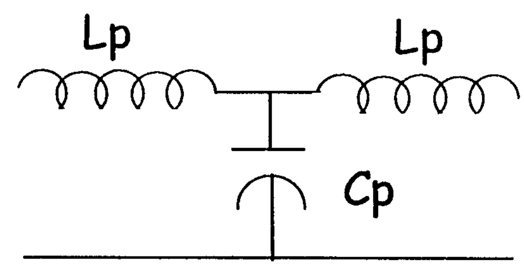


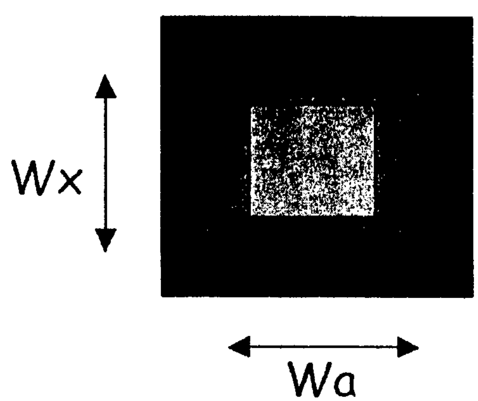
Microstrip Line
Shorting Via
Coupling Slot
Evanescent Mode Cavity
Capacitive Post

University of

Modeling

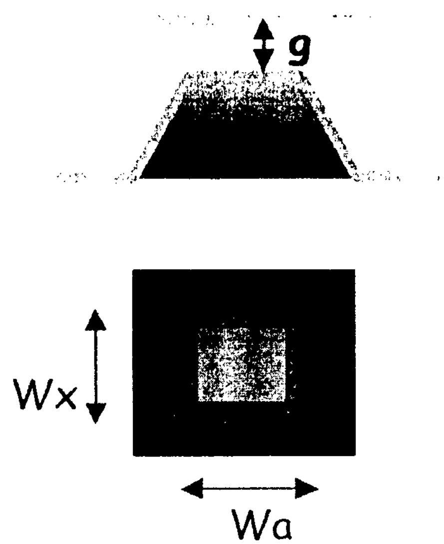


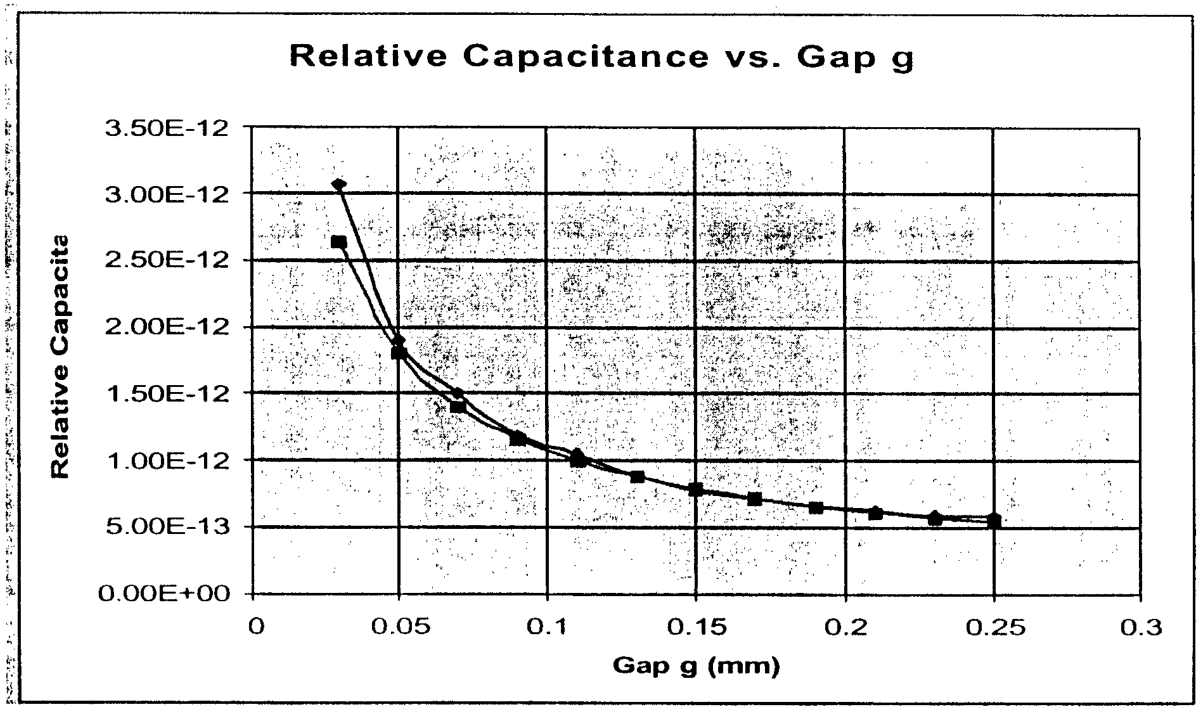




$$Cpost = \frac{\mathbf{K} * \in^{o} * [(\mathbf{Wa})^{0.63} * (\mathbf{Wx})^{0.33}]}{(\mathbf{1 - g})}$$

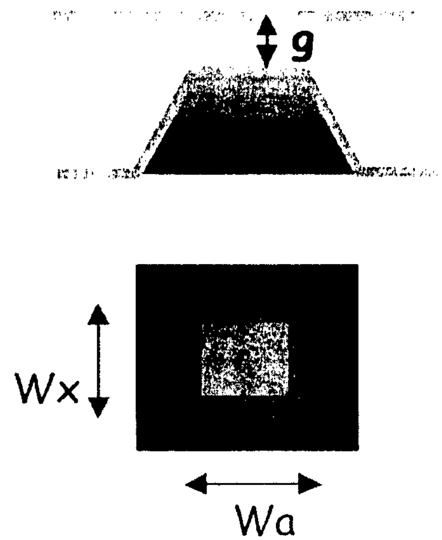
$$Lp = A*[Wa*Wx*(1-g)] + B$$

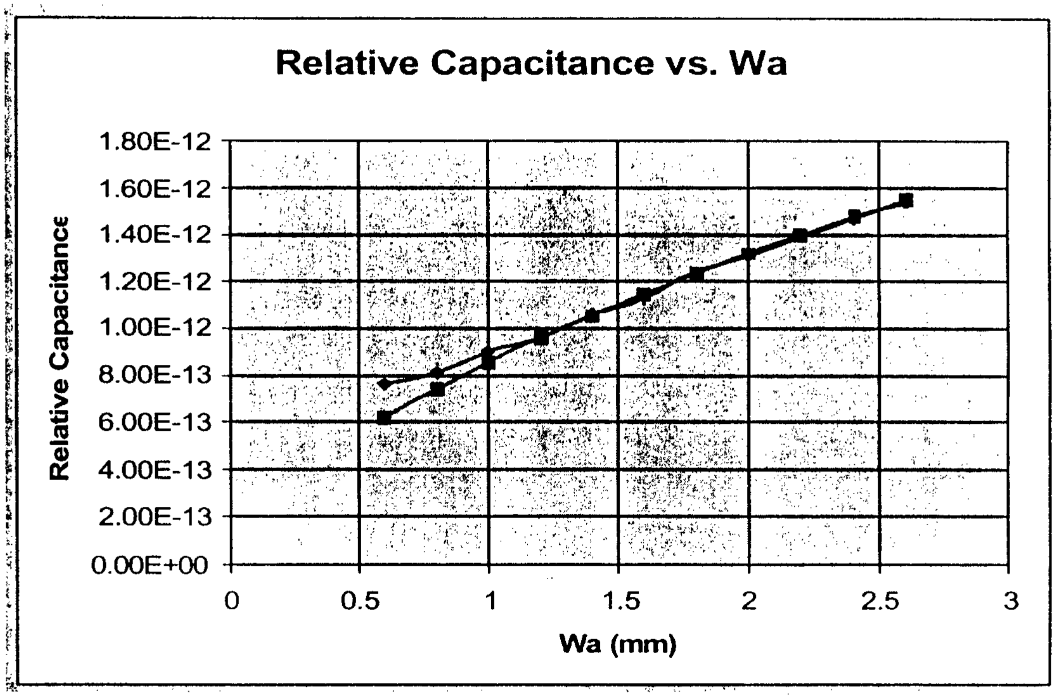




Quasi-Static

Full-Wave





Quasi-Static

Full-Wave

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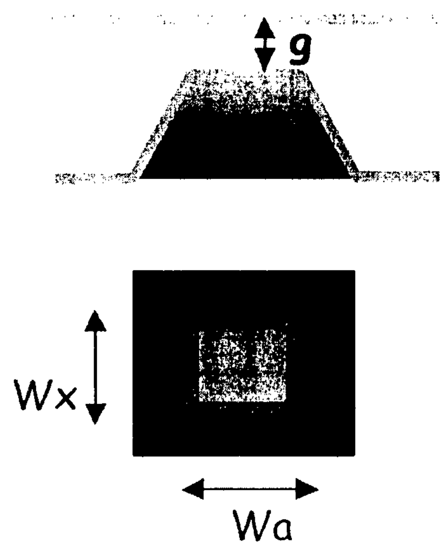
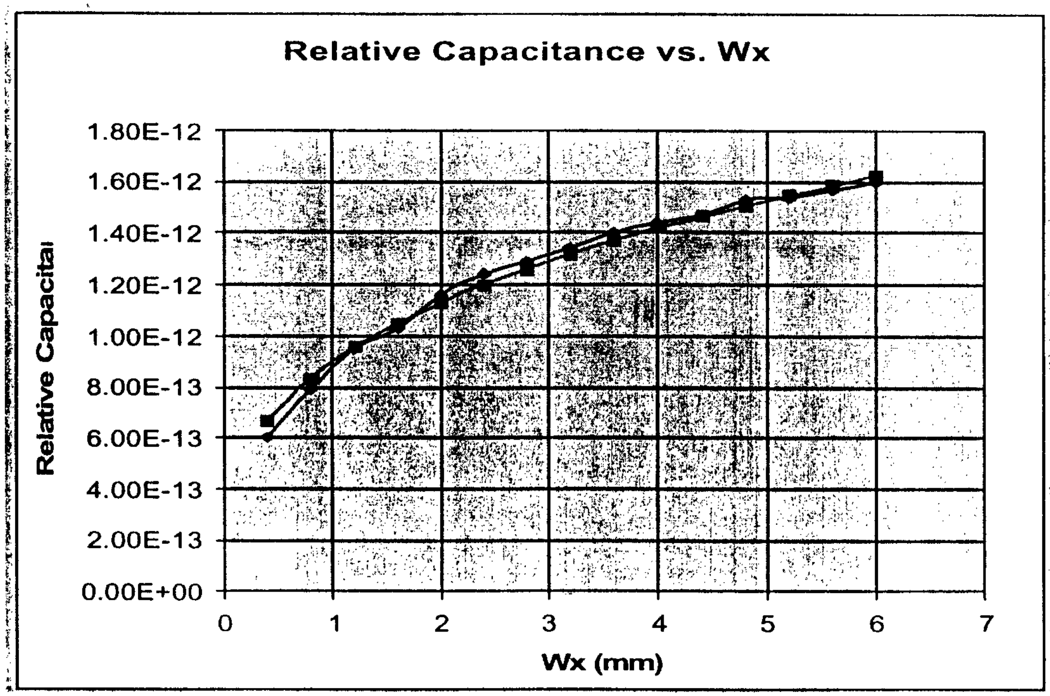
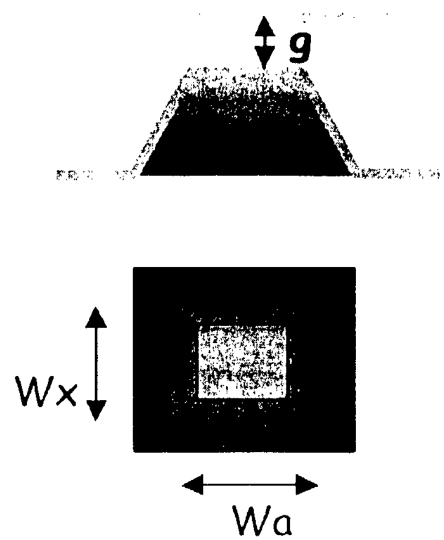
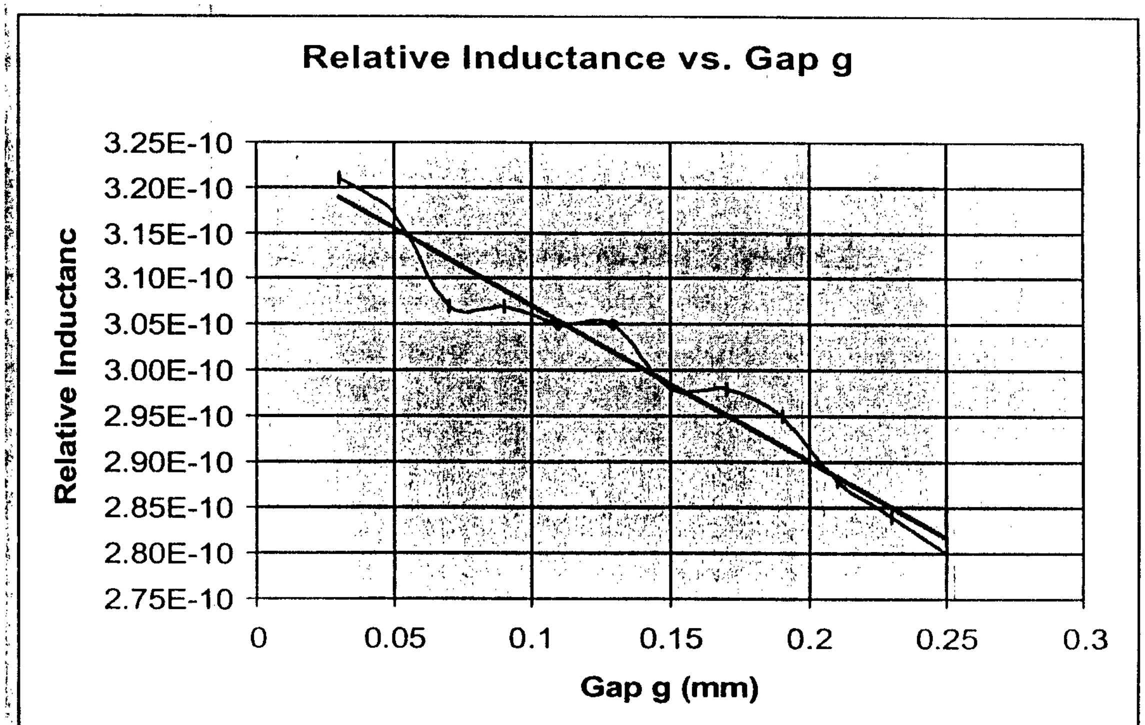




Quasi-Static

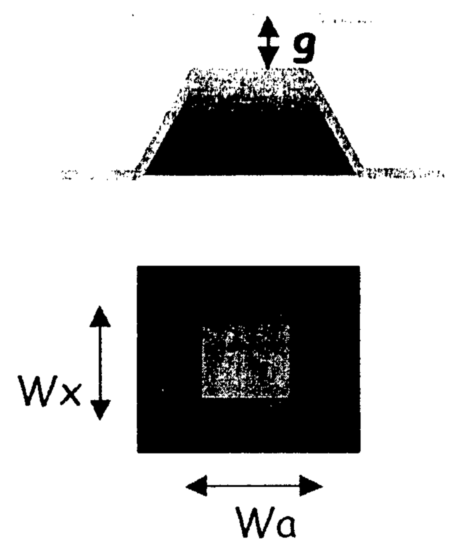
Full-Wave

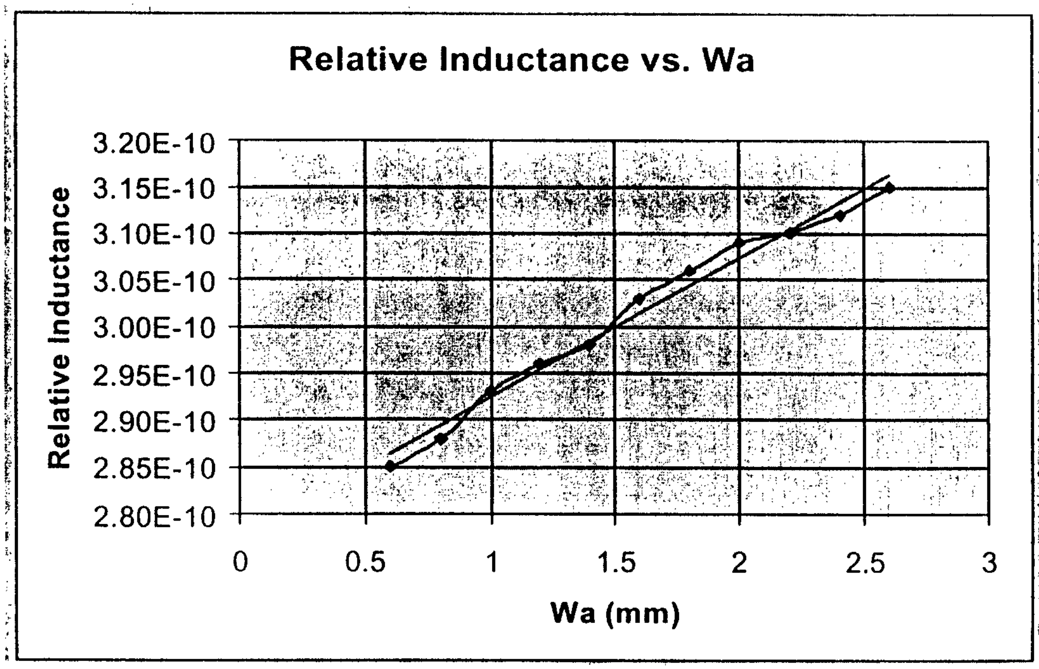




Quasi-Static

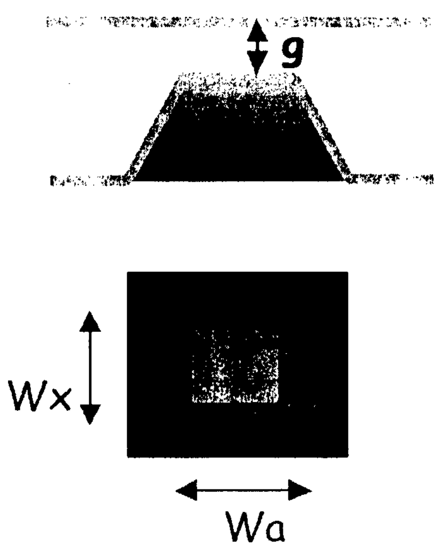
Full-Wave

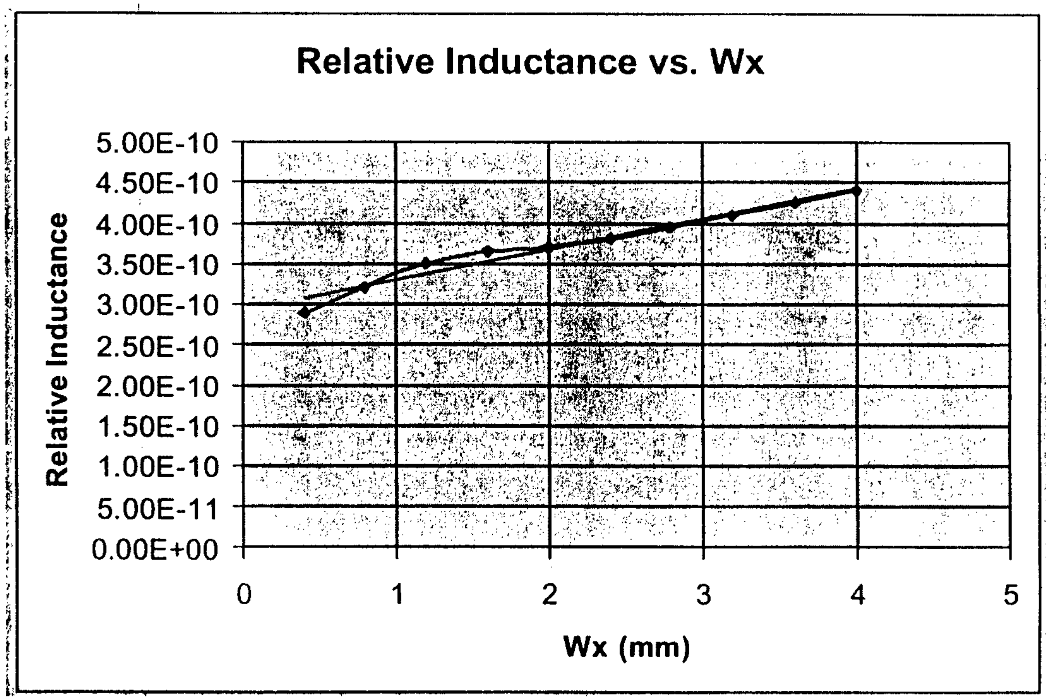




Quasi-Static

Full-Wave

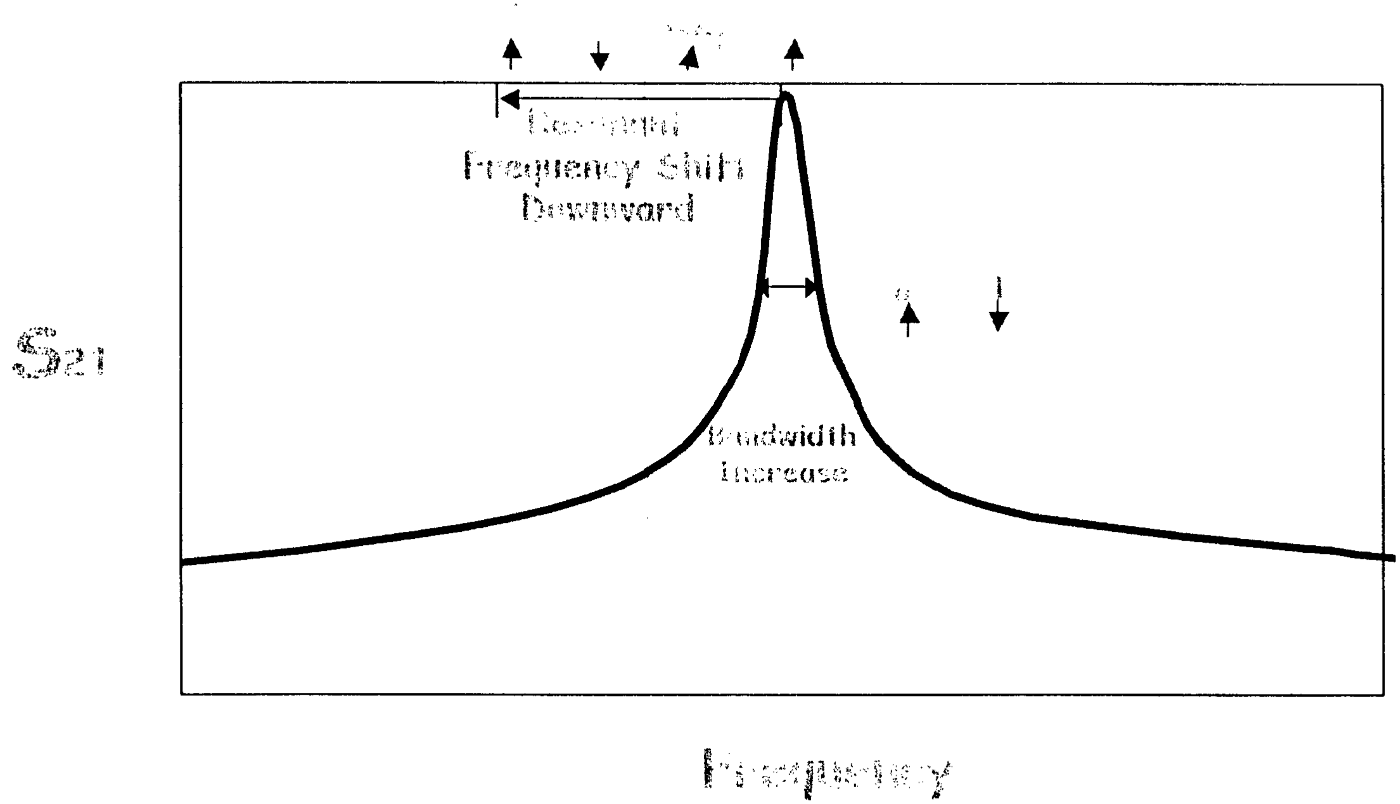




Quasi-Static

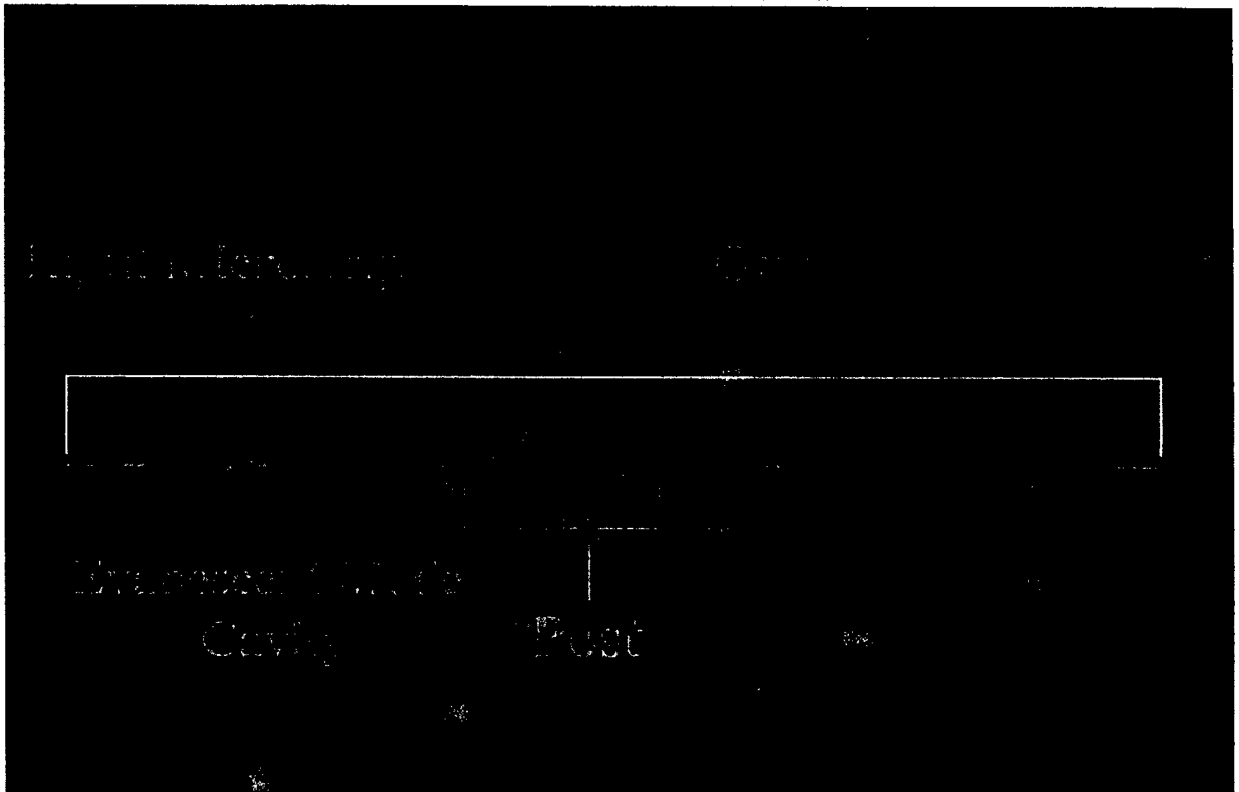
Full-Wave

Insertion Trends



[illegible]

Mode [illegible]



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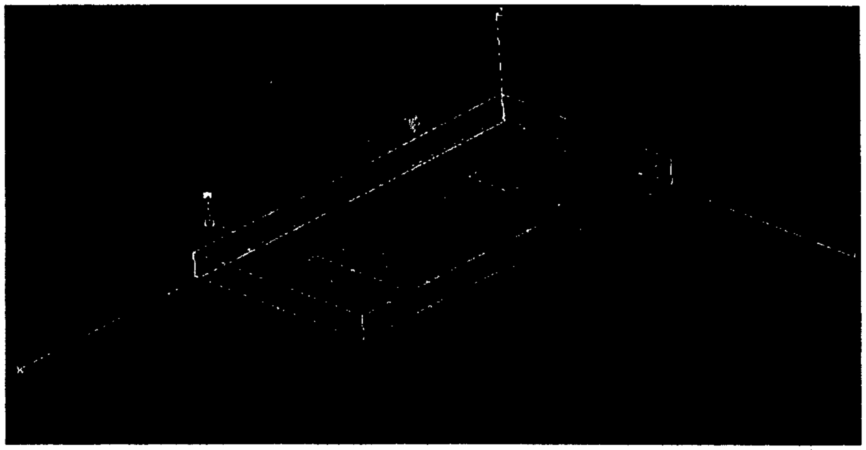
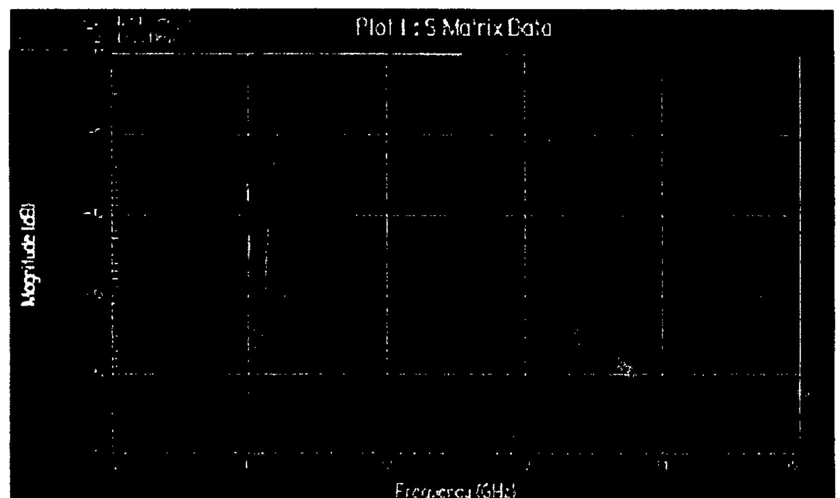


10 mm x 7 mm x 0.5 mm
With a Q of 500

S-Parameters



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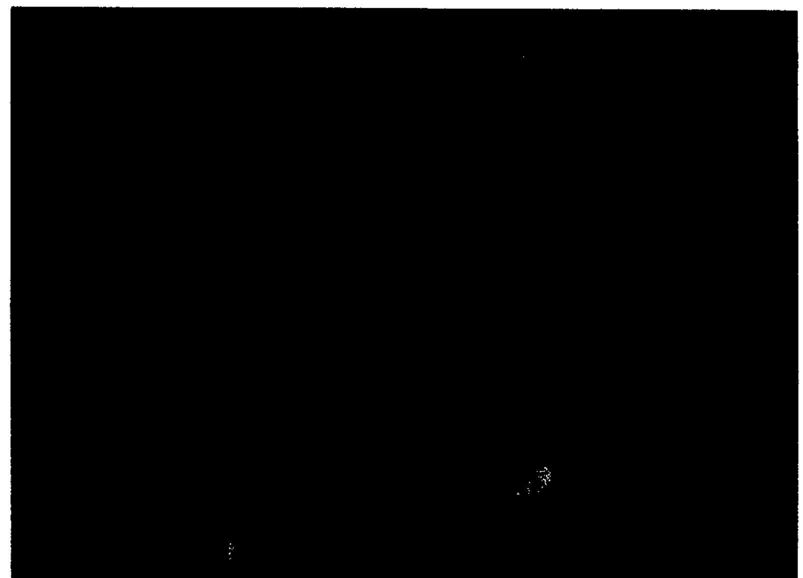
Single Pole [illegible] Mode [illegible] (3 GHz)

Microwave Model



20mm x 17mm x 2mm

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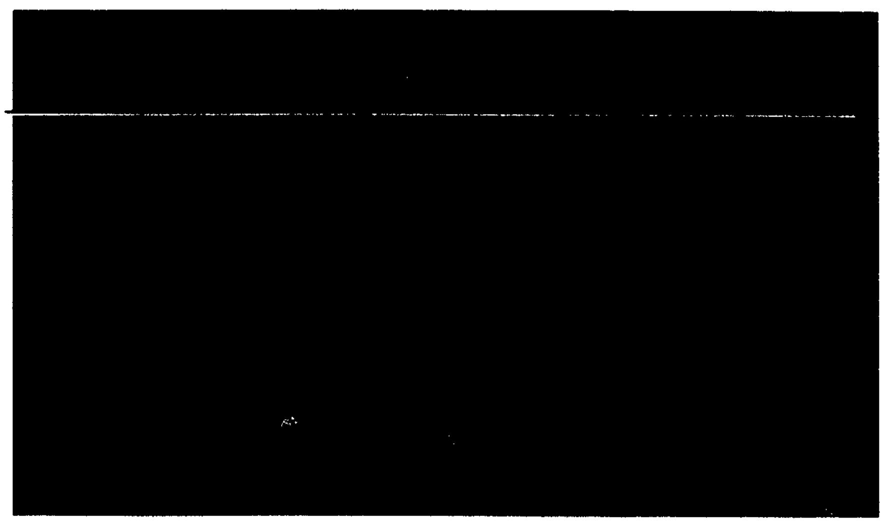
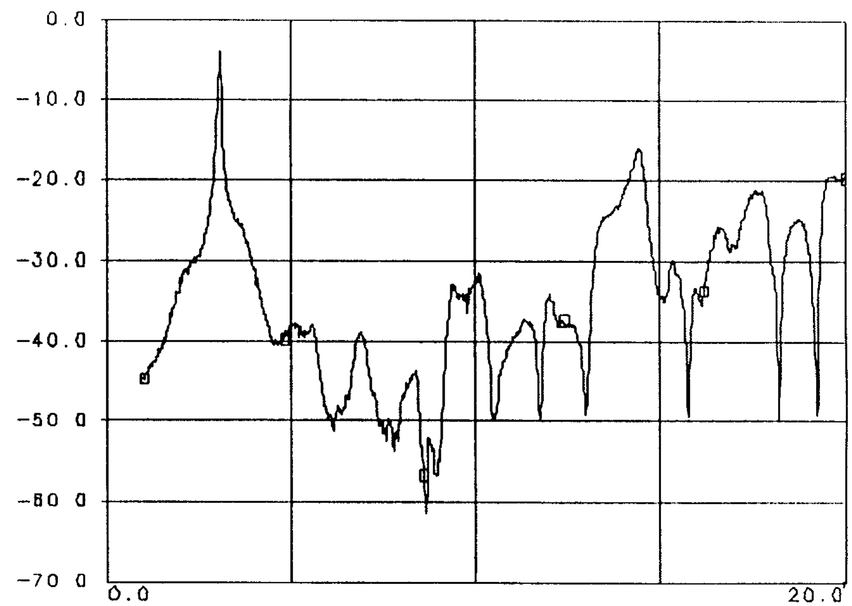
Single Pole Evanescent Mode Filter





Microwave Model

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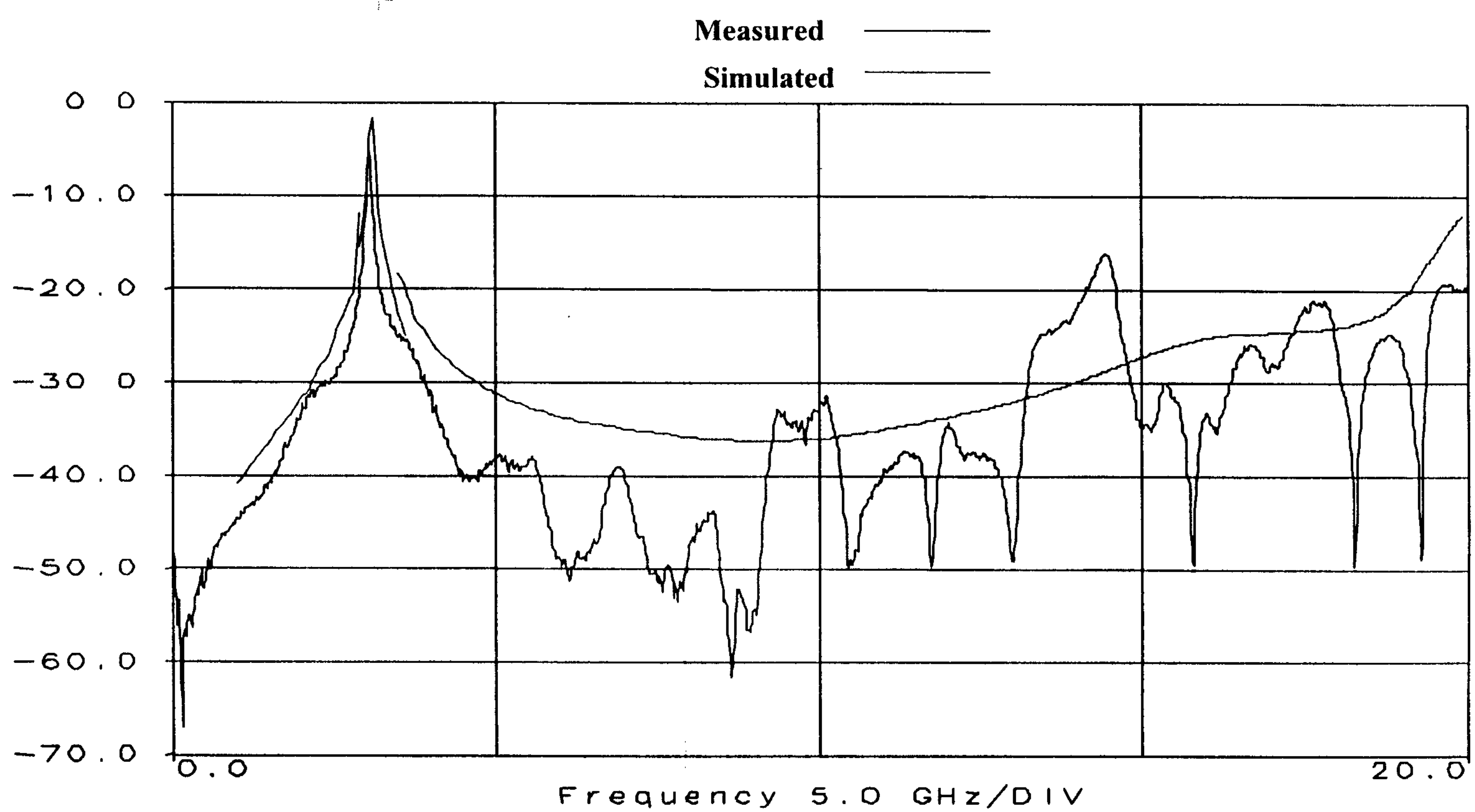

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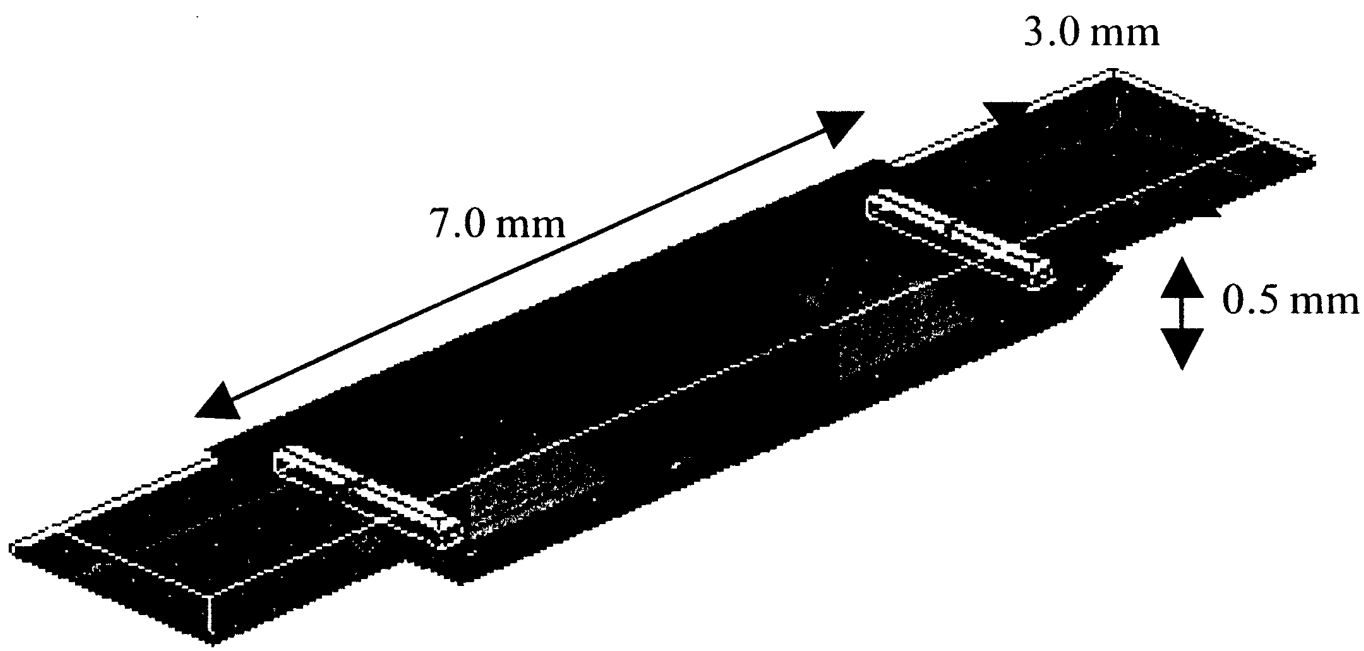

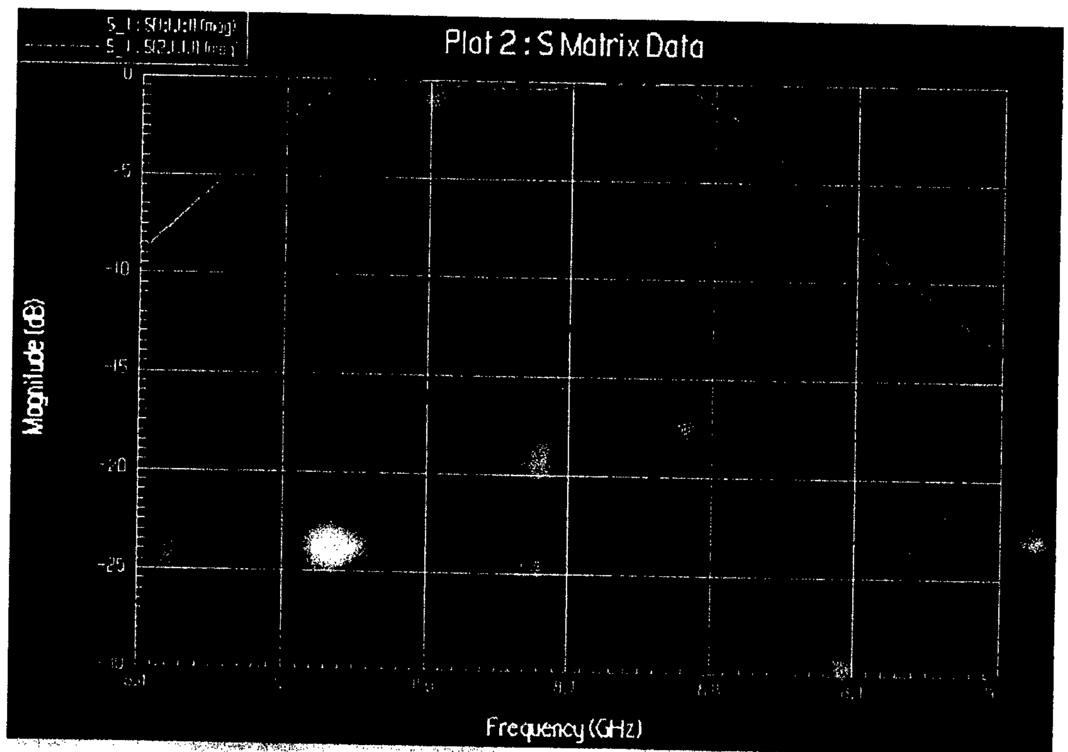
Plot 2 : S Matrix Data
Magnitude (dB)
Frequency (GHz)
0
-5
-10
-15
-20
-25

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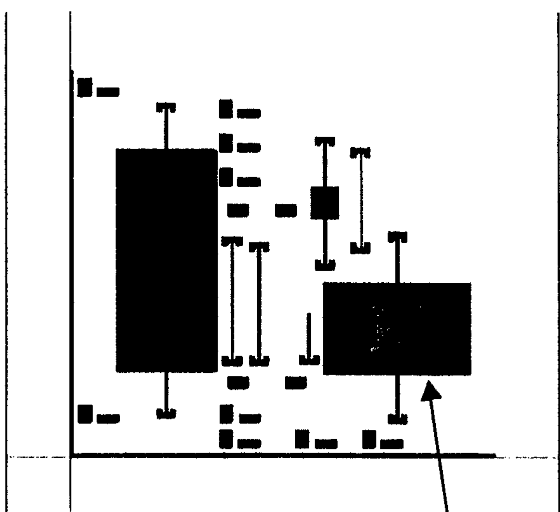
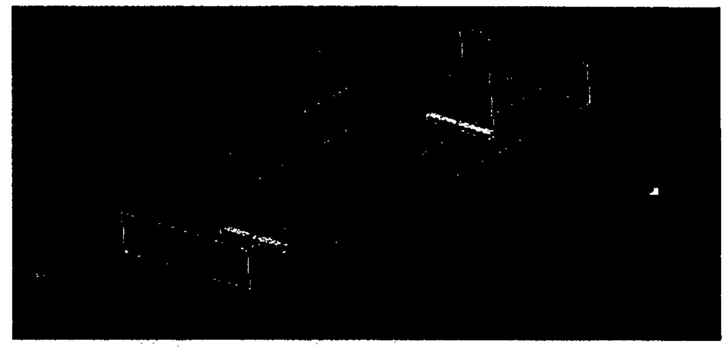
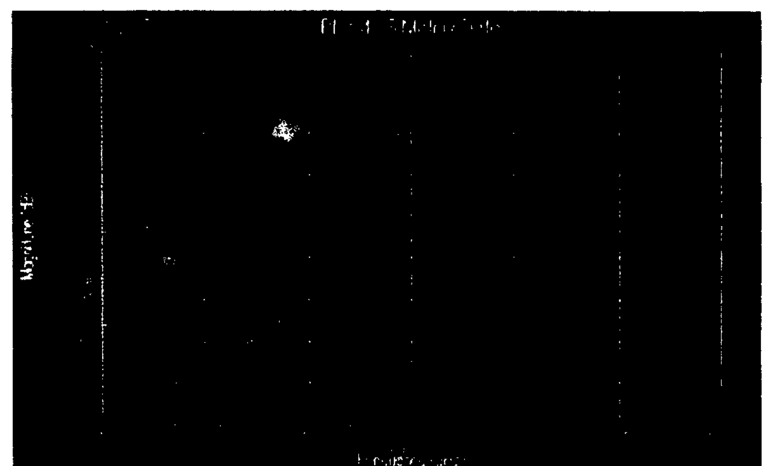
Silicon Micromachined

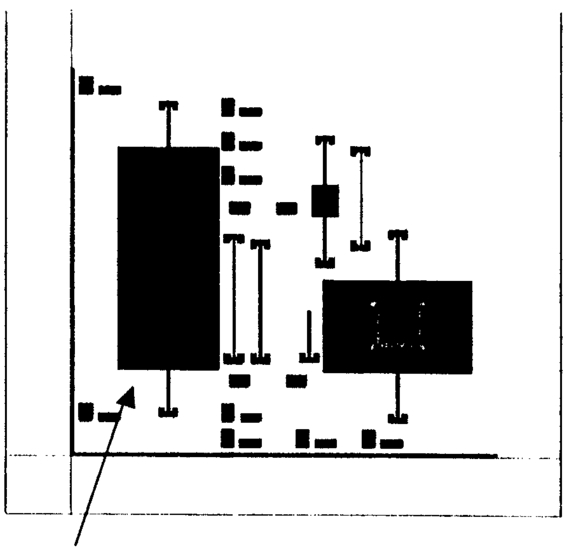


Resonator on Mask

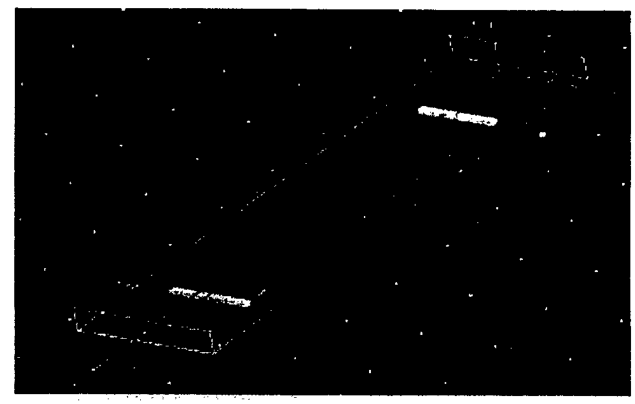
Expected Q =

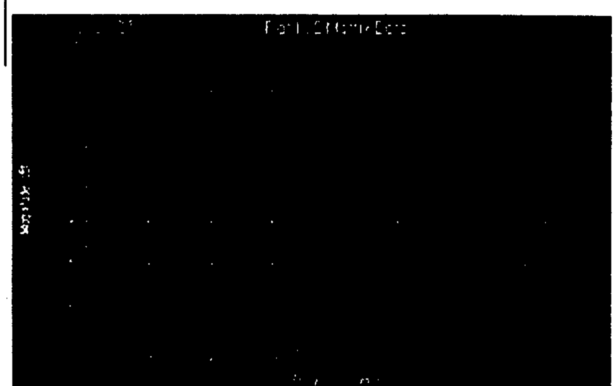




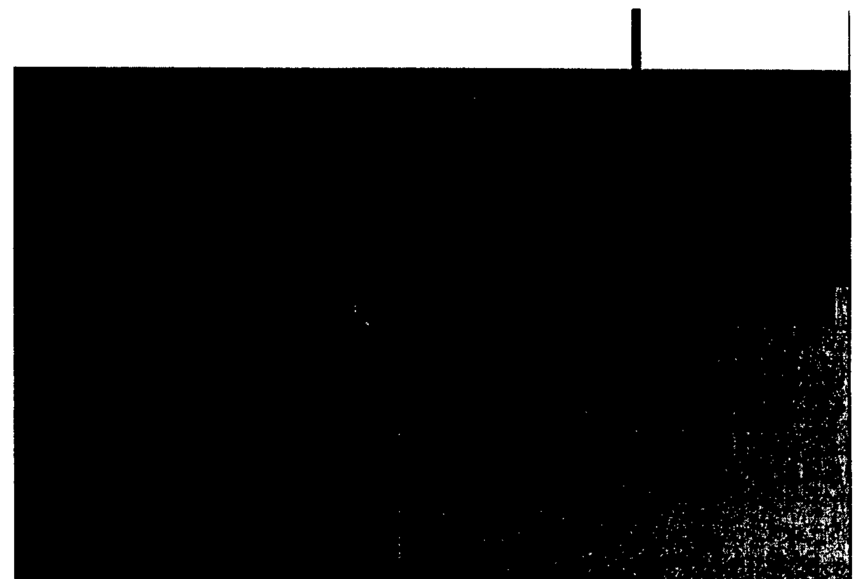


Bandpass Filter on Mask



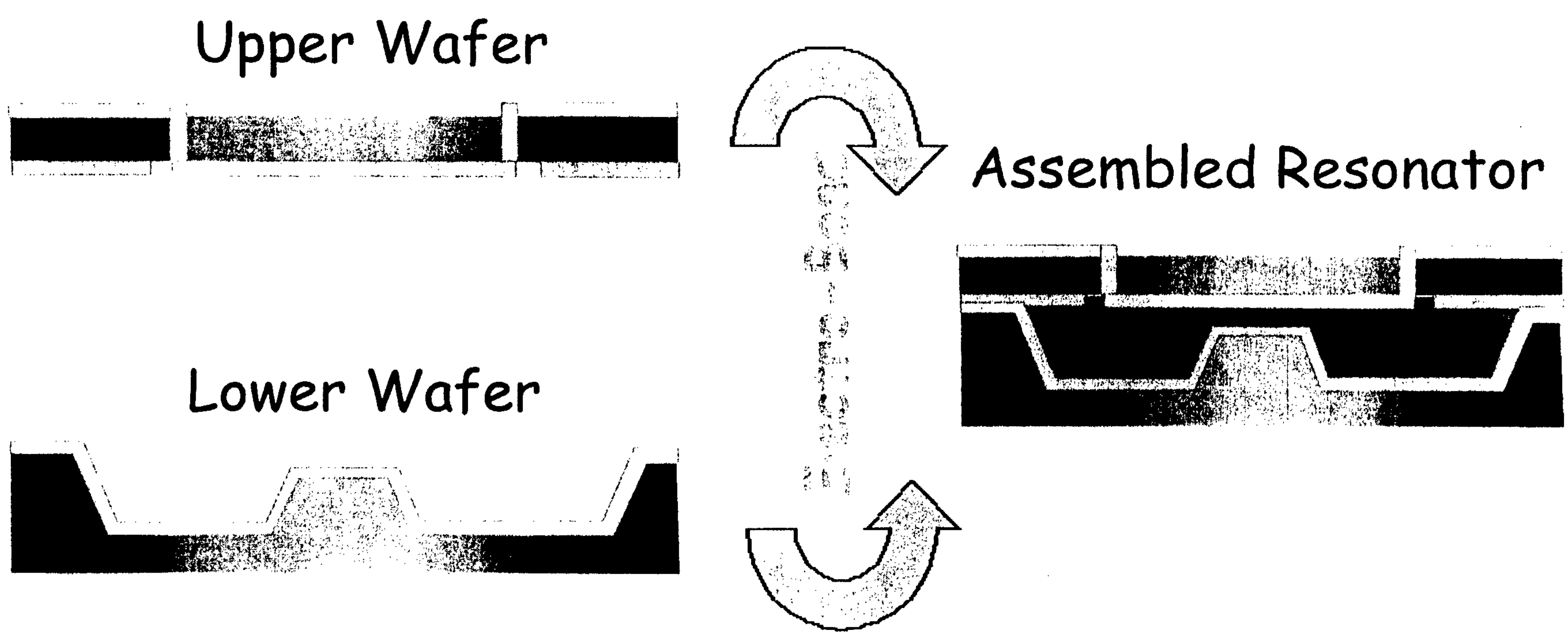


Picture of Actual Squares



Compensation Square

Rule is a=1.5*Etch Depth


Upper Wafer
Lower Wafer
Assembled Resonator

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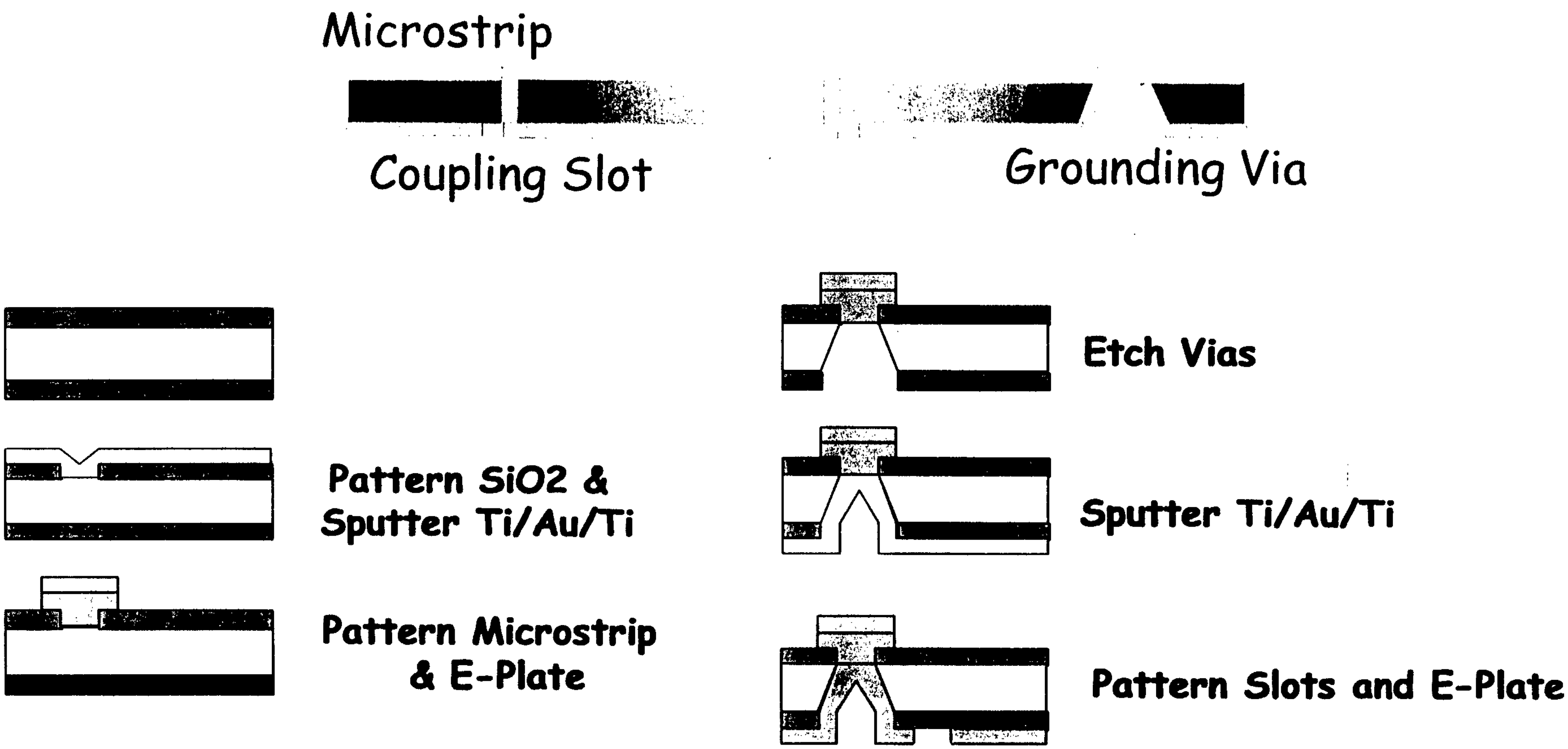

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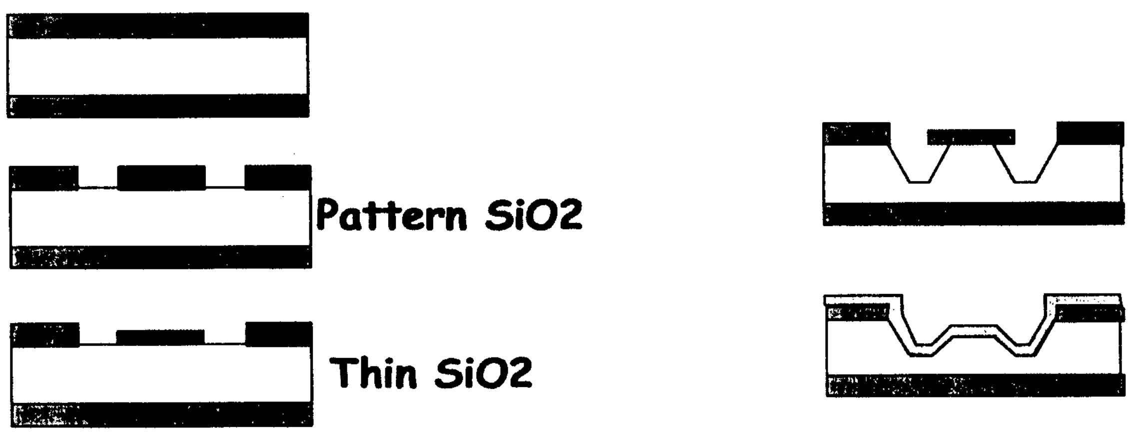
Fabrication of [illegible] Wafer



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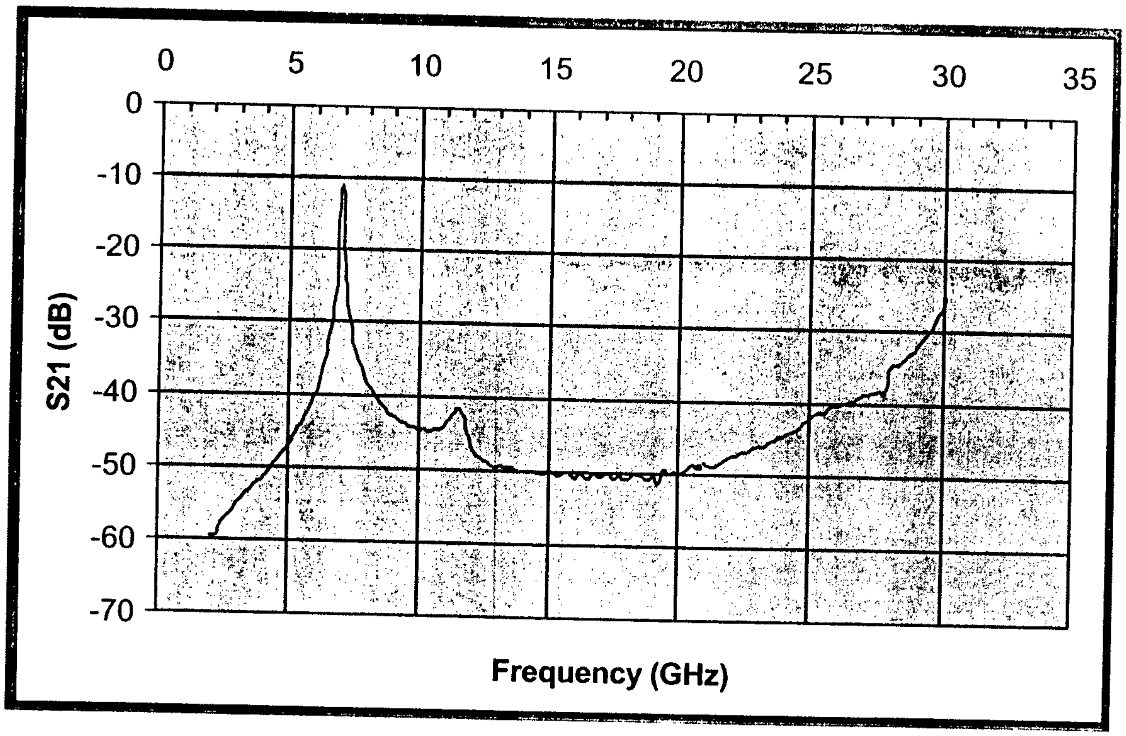

Insertion Loss due to Lines 0.? dB, Ql=90, Qu=130

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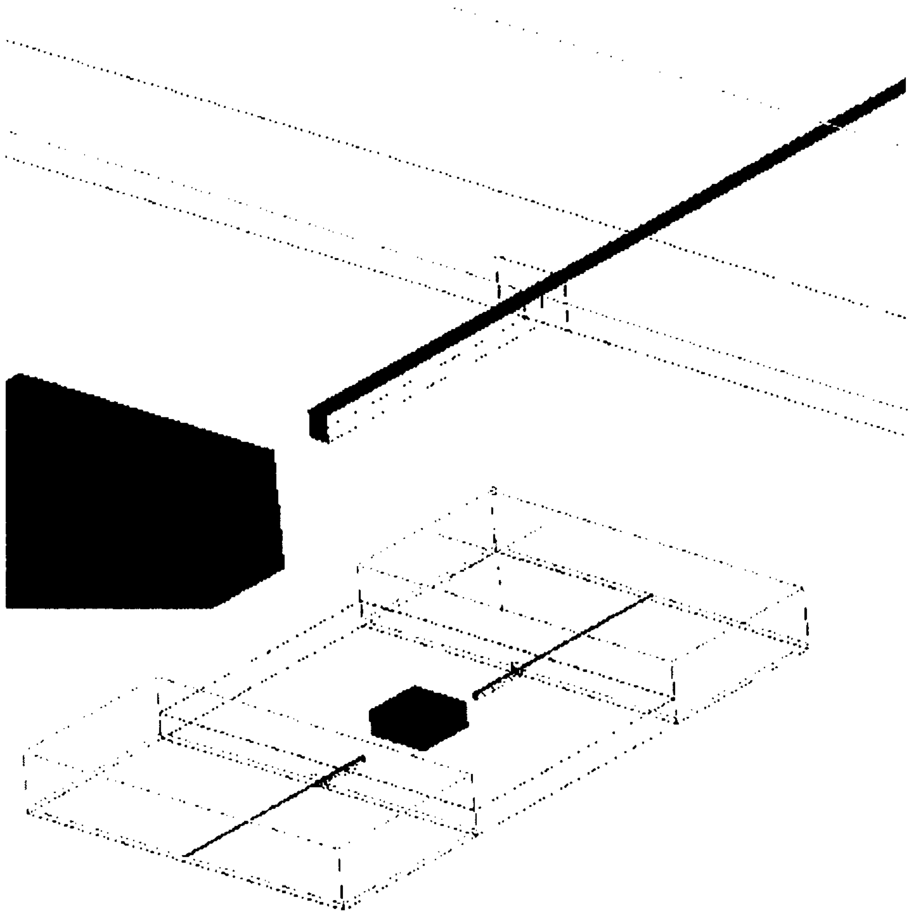

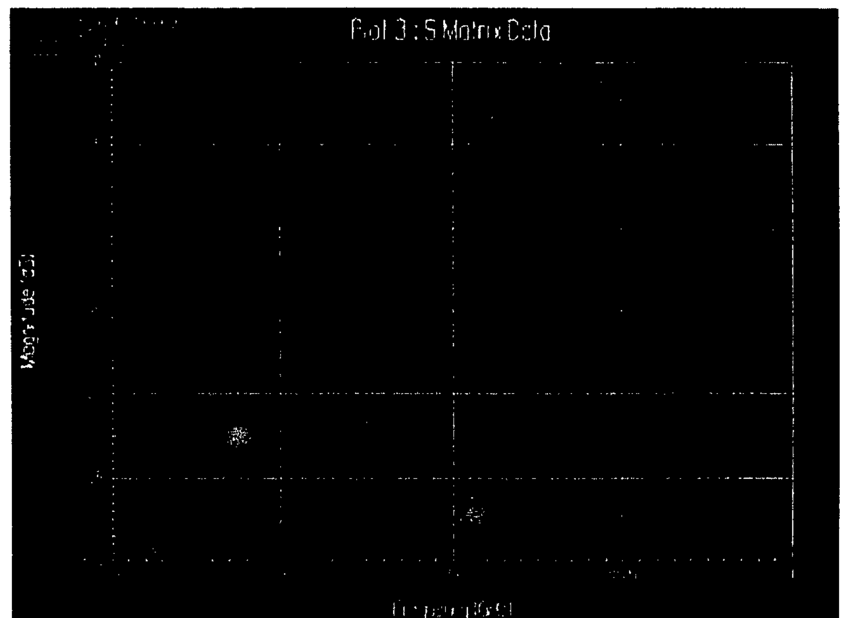

Size 6 by 4.5

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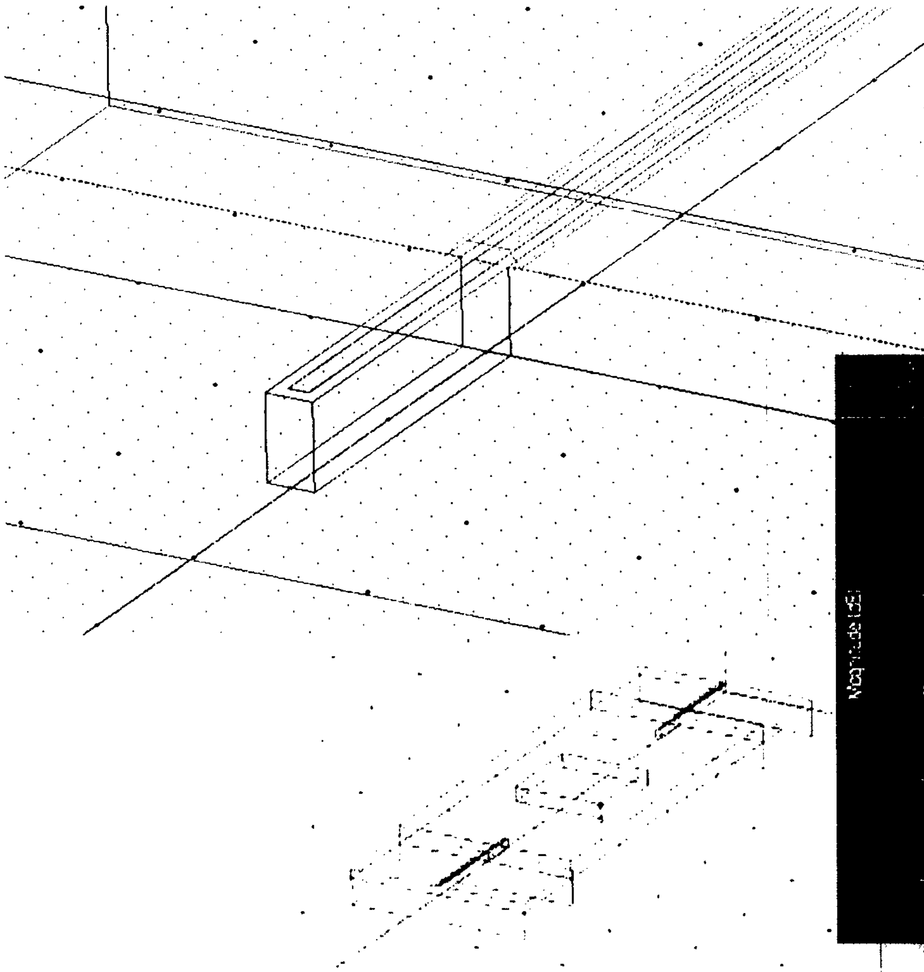

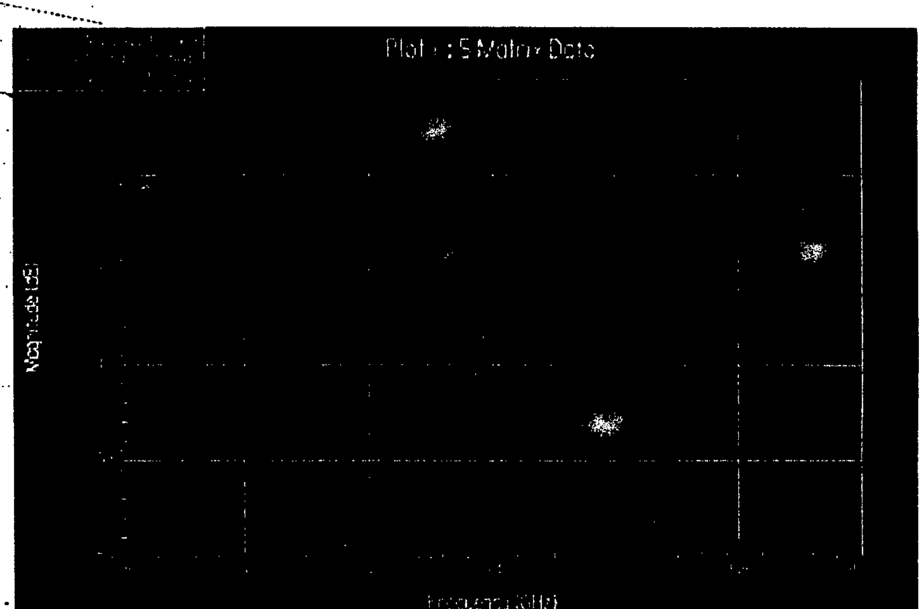

Size 20 by 10 by [illegible]

- Tuning External Coupling
- Tuning Post Capacitance
- Tuning of Internal Coupling or Evanescent Mode Sections

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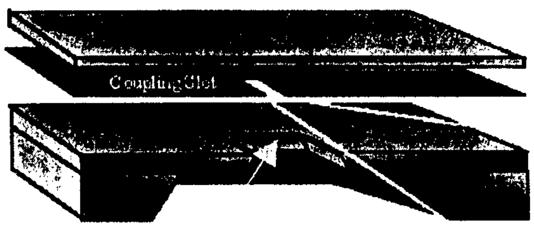
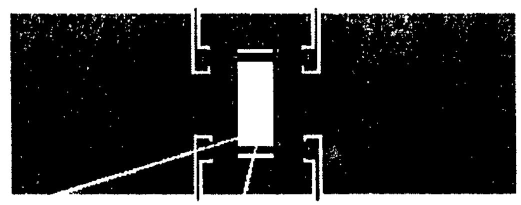
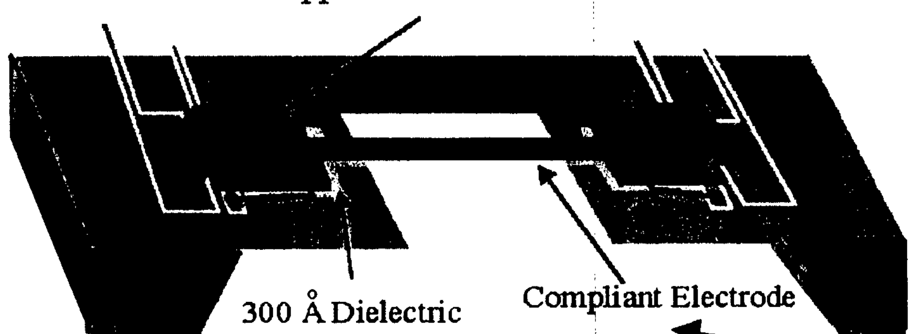


Evanescent Mode
Cavity

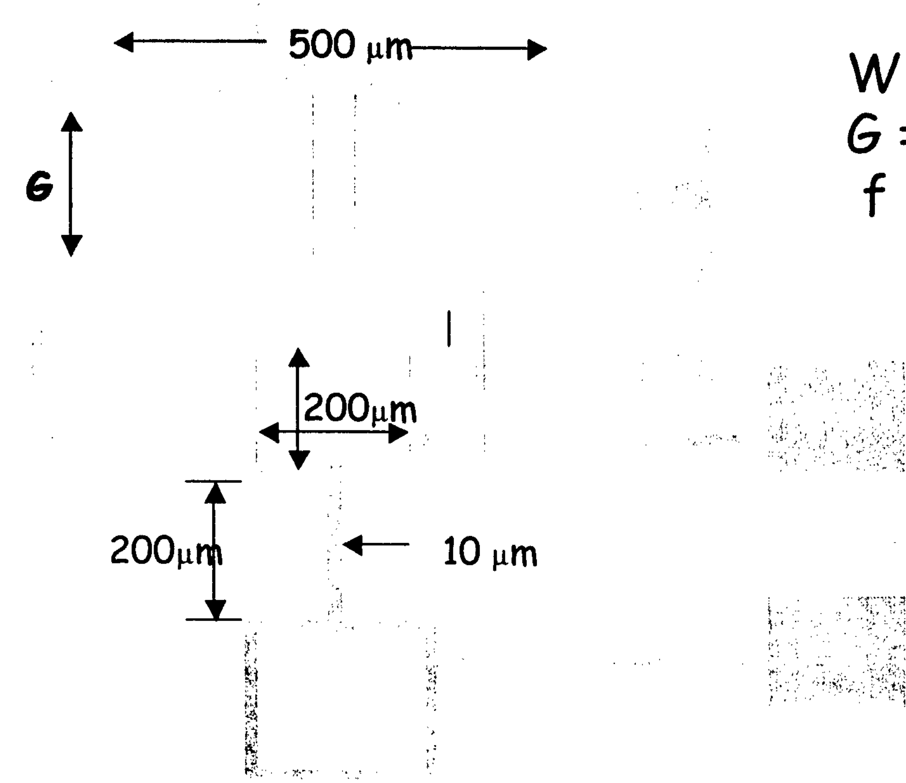
Coupling Slot with Switches



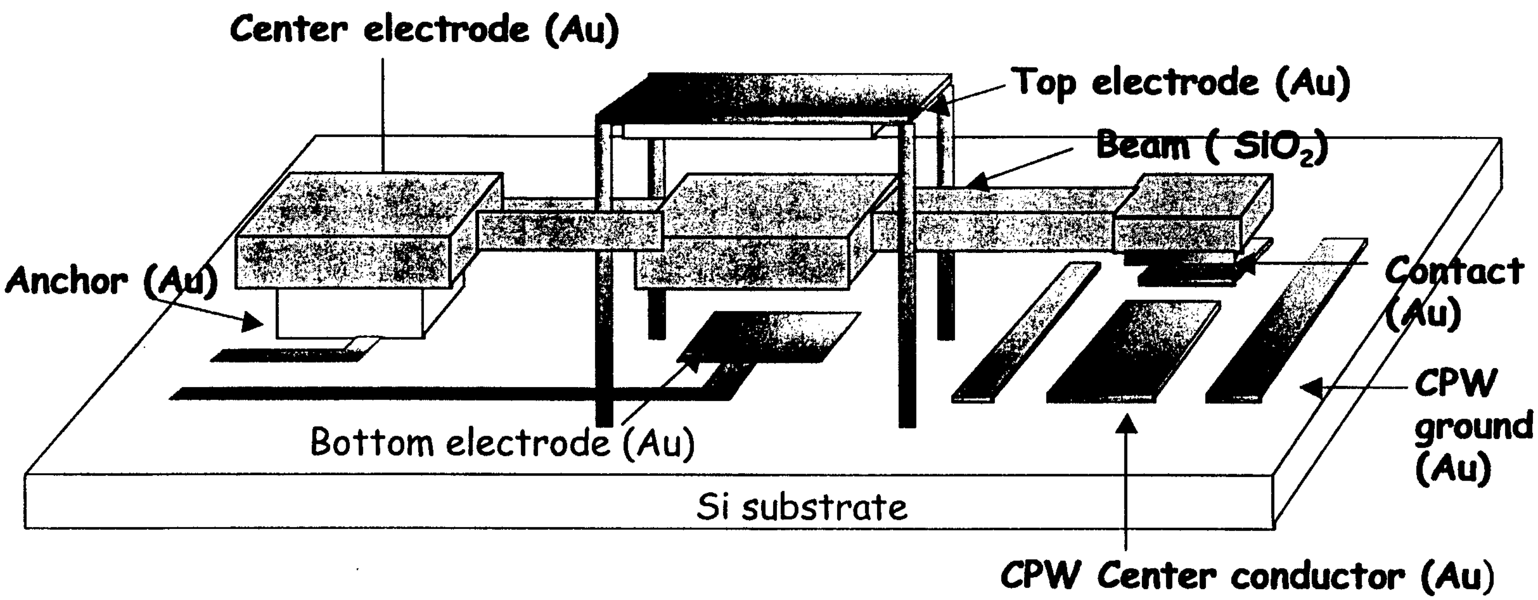


MEMS Switch

Tuning Input Slot External Coupling via a Cantilever Beam



$W = 60\ \mu m$
$G = 40\ \mu m$
$f = 30\ GHz$



Center electrode (Au)
Top electrode (Au)
Beam (SiO_2)
Anchor (Au)
Contact (Au)
CPW ground (Au)
Bottom electrode (Au)
Si substrate
CPW Center conductor (Au)

Spring constant

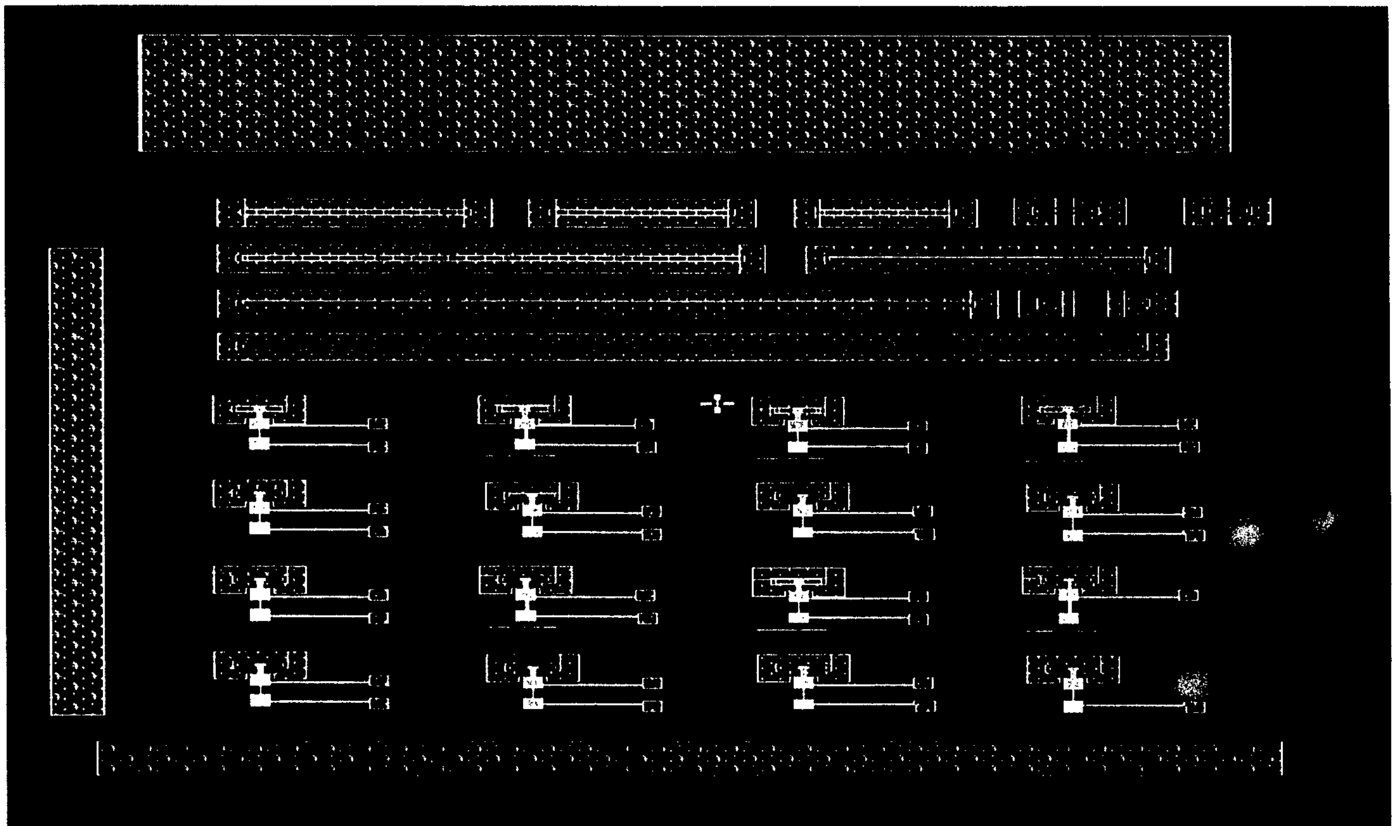
$$k = \frac{wEt^3}{4l^3}$$

Beam length (µm)	Beam width = 10(µm)	Beam width = 20(µm)
180	0.24 N/m	0.48 N/m
200	0.18 N/m	0.35 N/m
220	0.13 N/m	0.26 N/m
240	0.10 N/m	0.20 N/m

Pull-in Voltage

$$Vpi = \sqrt{\frac{8kd^3}{27\varepsilon_0 A}}$$

Beam length (µm)	Beam width = 10(µm)	Beam width = 20(µm)
180	3.59 V	5.07 V
200	3.06 V	4.33 V
220	2.64 V	3.73 V
240	2.31 V	2.27 V



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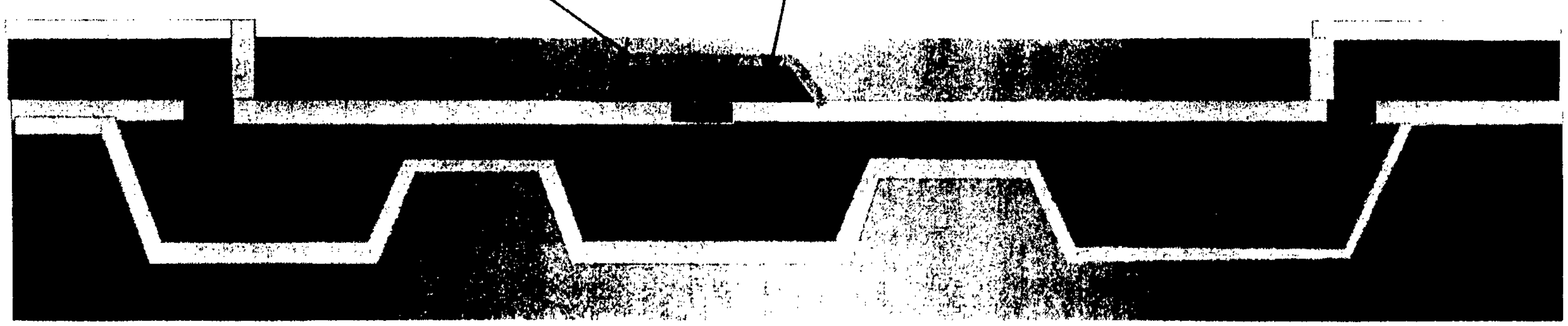
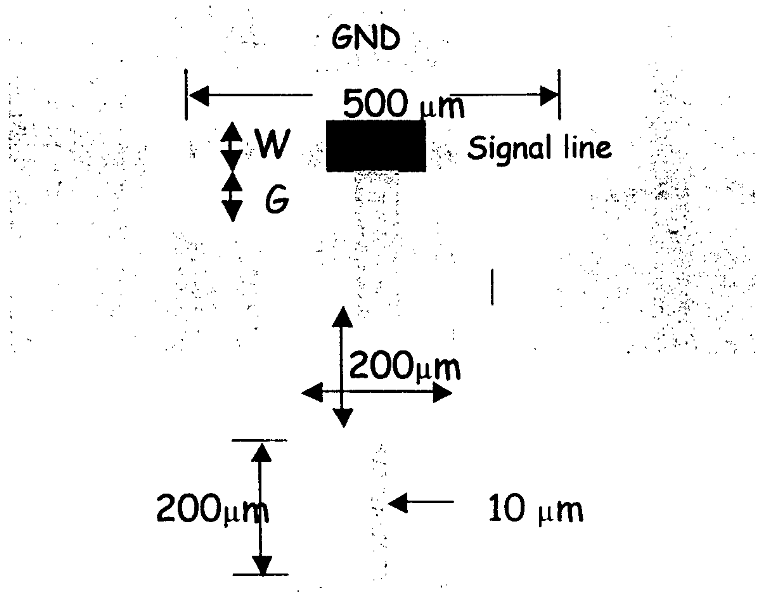
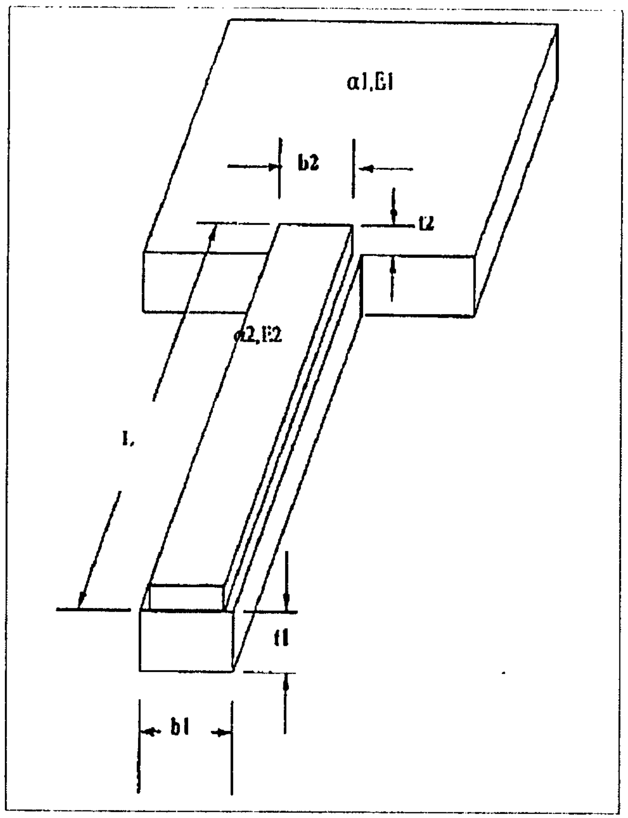




$W = 60\ \mu m$
$G = 40\ \mu m$
$f = 30\ GHz$



- Tip deflection

$$d = \frac{kL^2}{2}$$

$$k = \frac{1}{r} = \frac{6b_1b_2E_1E_2t_1t_2(t_1+t_2)(a_2-a_1)\Delta T}{(b_1E_1t_1^2)^2 + (b_2E_2t_2^2)^2 + 2b_1b_2E_1E_2t_1t_2(2t_1^2+3t_1t_2+2t_2^2)}$$

- Max force at the tip of cantilever

$$F = \frac{3EId}{L^3}$$

- Conversion factors :

$$\gamma = \frac{d}{\Delta T}$$ (e.g. 0.1 μm/K)

$$\gamma_E = \frac{d}{P_{IN}}$$ (Typically 0.5-1 μm/mW)

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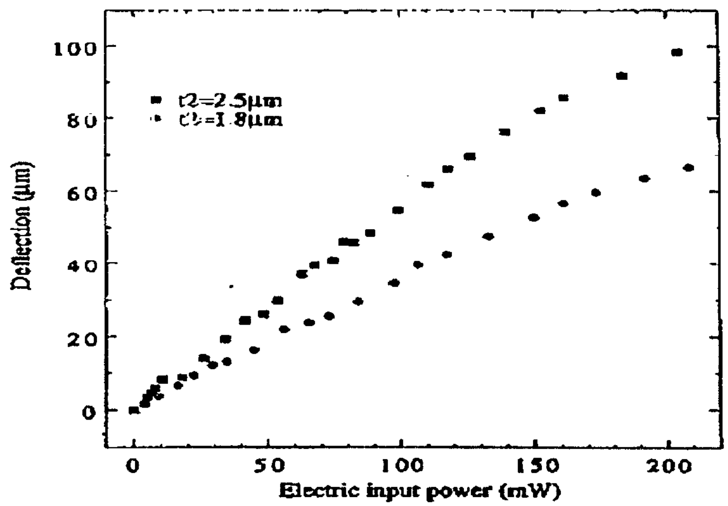
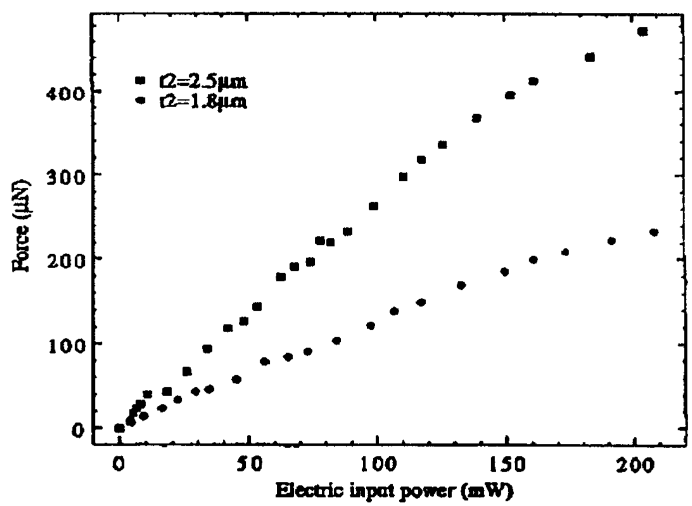
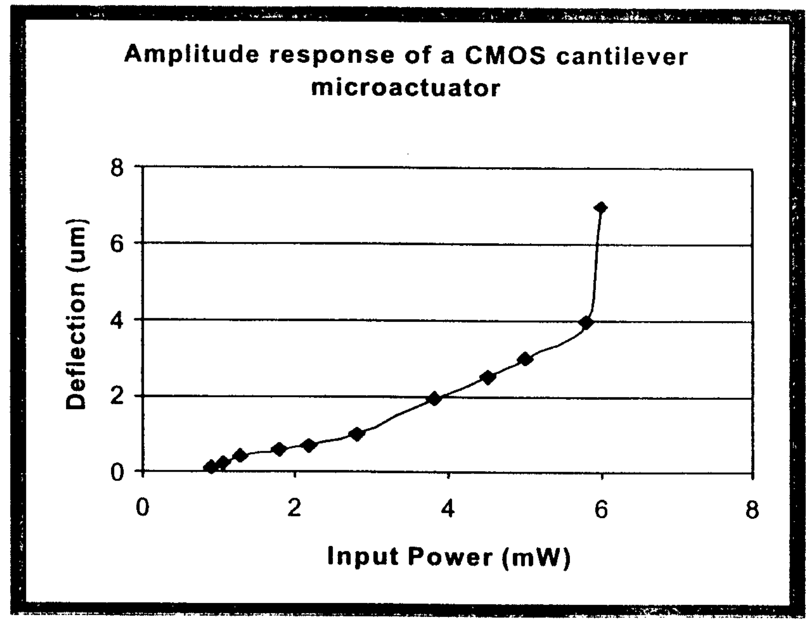
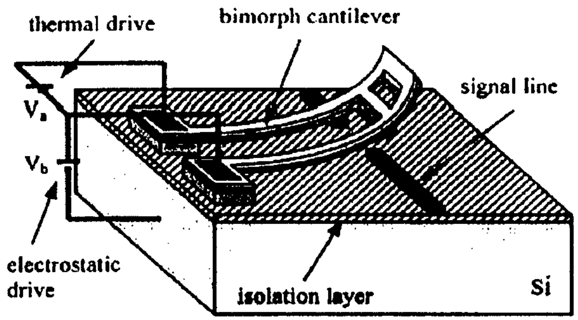
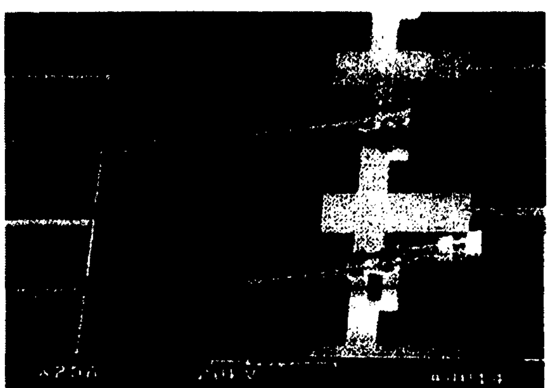




L = 170 µm w = 10 µm





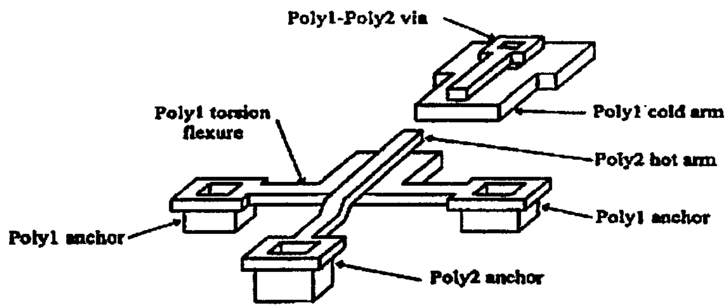


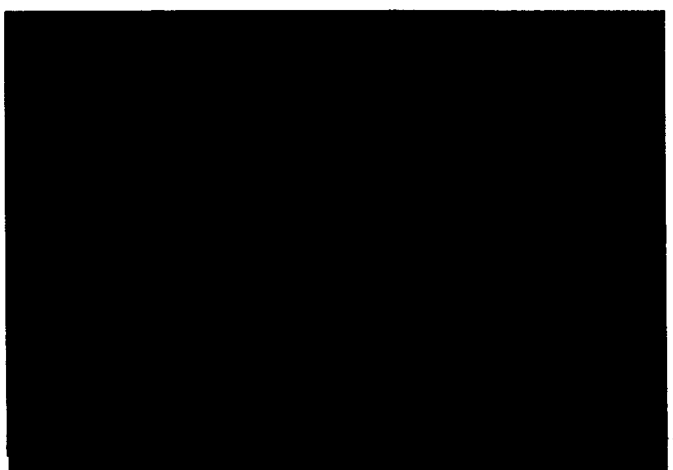
Basic Characteristics

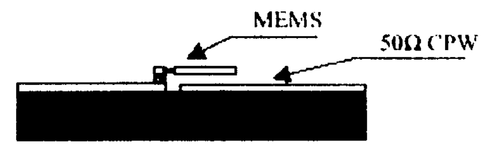
- Gold-to-gold electrical contact
- R_{ON} = 0.6 - 0.8 Ω
- L = 328 μm, w = 16 μm
- Combined thermal and electrostatic actuation
- Beam : $TaSi_2/SiO_2$
- Beam deflection : not reported
- Power (min) : 8.0 mW / 20 V
- Life time :
  a) 10^6 cycles (hot switching @ 2 mA/2KHz),
  b) only several cycles (sticking) @ 5 mA/low frequency

Case 2 : Cantilever beam used for tunable capacitor

(K.C. Gupta et. al., MTT [illegible])







Basic Characteristics

- Variable capacitor (5:1)
- No metal-to-metal contact
- L = 300 μm, w = 200 μm
- thermal actuation
- Beam : poly-1/poly-2
- Beam deflection : 1.6 μm
- Power : not reported (volt : 5V)
- Life time : not reported

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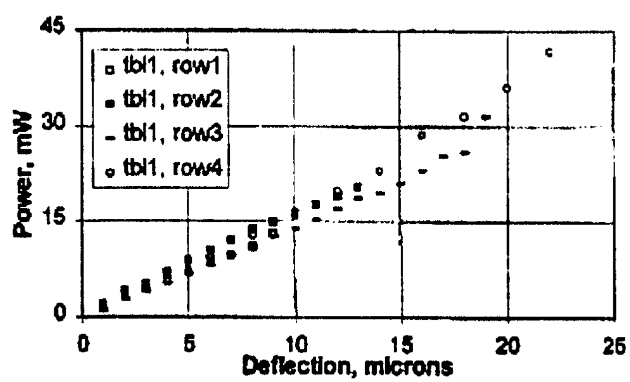
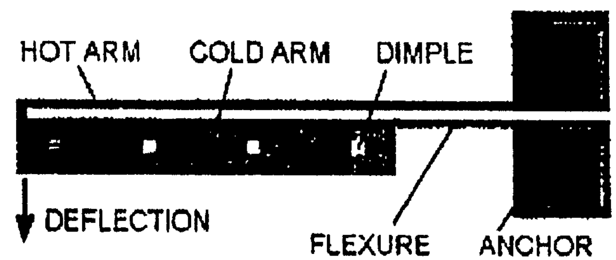
Case 3 : Lateral cantilever beam

Table 1
Best dimensions for unloaded or lightly loaded actuators

Length	Hot arm width	Flexure length	Gap width	Max. deflection	Max. pow (mW)
150	1	30	1.5	9	13
200	1.5	50	1.5	13	21
250	1.5	80	1.5	19	32
300	2	75	1.5	22	42

All linear dimensions are in μm.

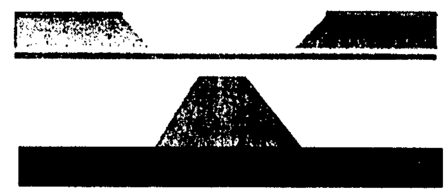




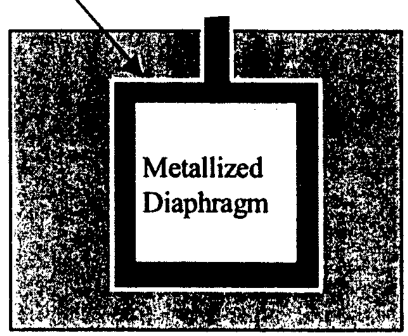
Basic Characteristics

- L = 220 μm, $w_{hot\ arm}$ = 2.5 μm
- thermal actuation
- Beam : poly hot/poly cold
- Beam deflection : ~ 15 μm
- Power : 15 mW
- Life time : 980 $\cdot 10^6$ cycles @2KHz

Diaphragm on Up Position

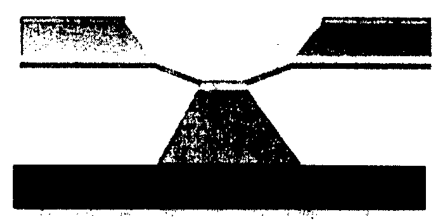


Slit Separating DC Electrodes



Metallized Cavity Walls

Diaphragm in On (DOWN) position



Diaphragm on Down Position

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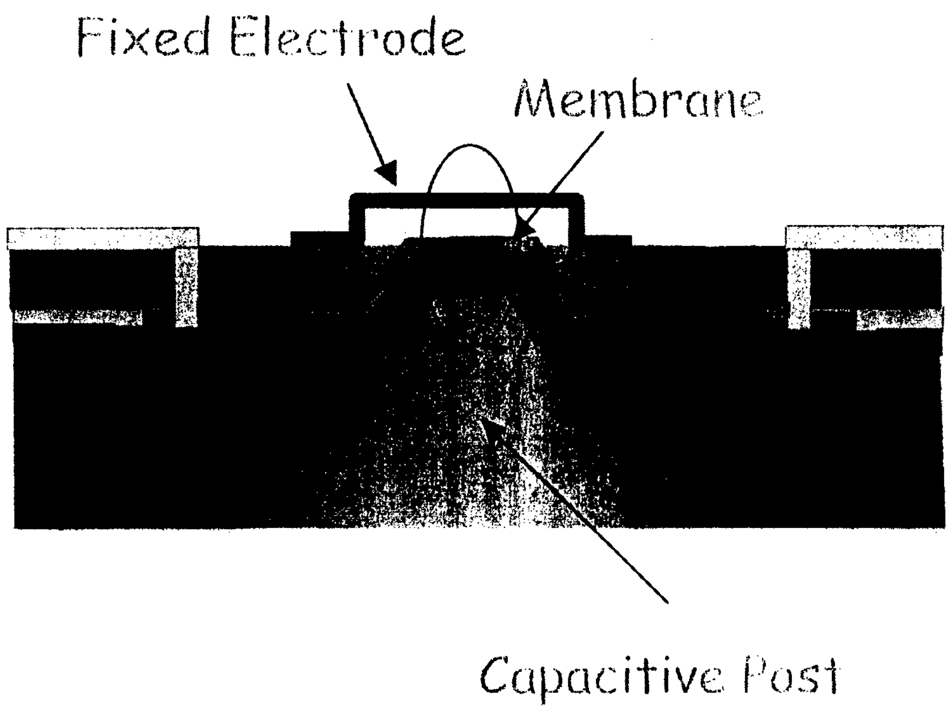
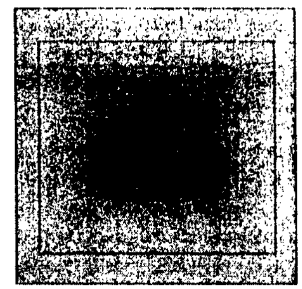
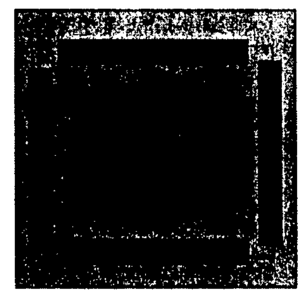
Types of Diaphragms

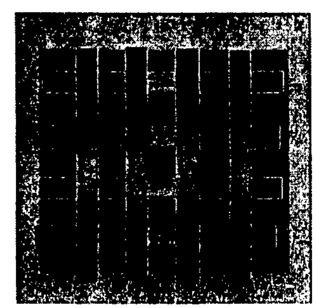




(a)



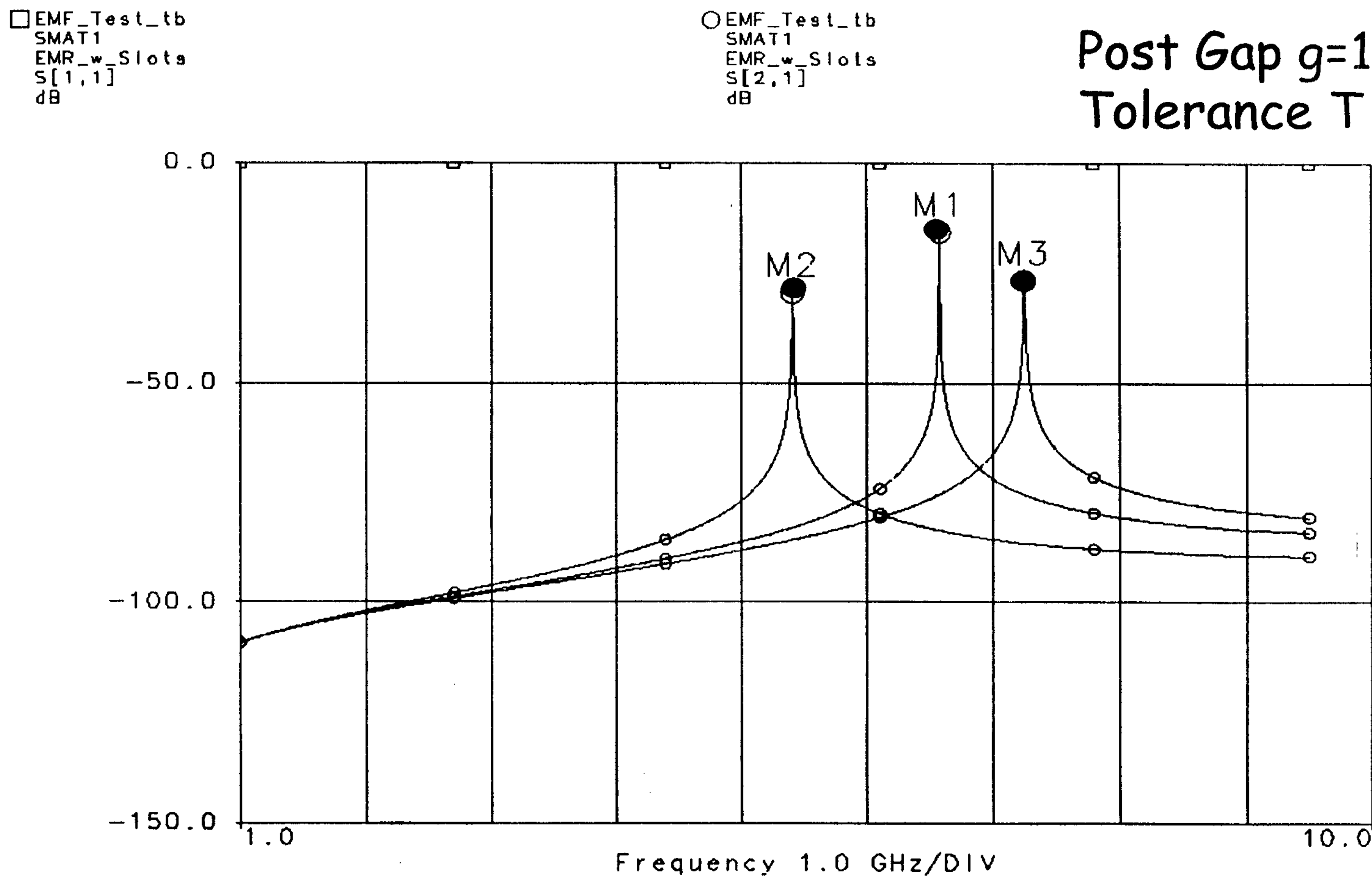
(b)



(c)

Fabrication Tolerance vs. Tuning

Post Gap $g=10\ \mu m$
Tolerance $T = 5\ \mu m$



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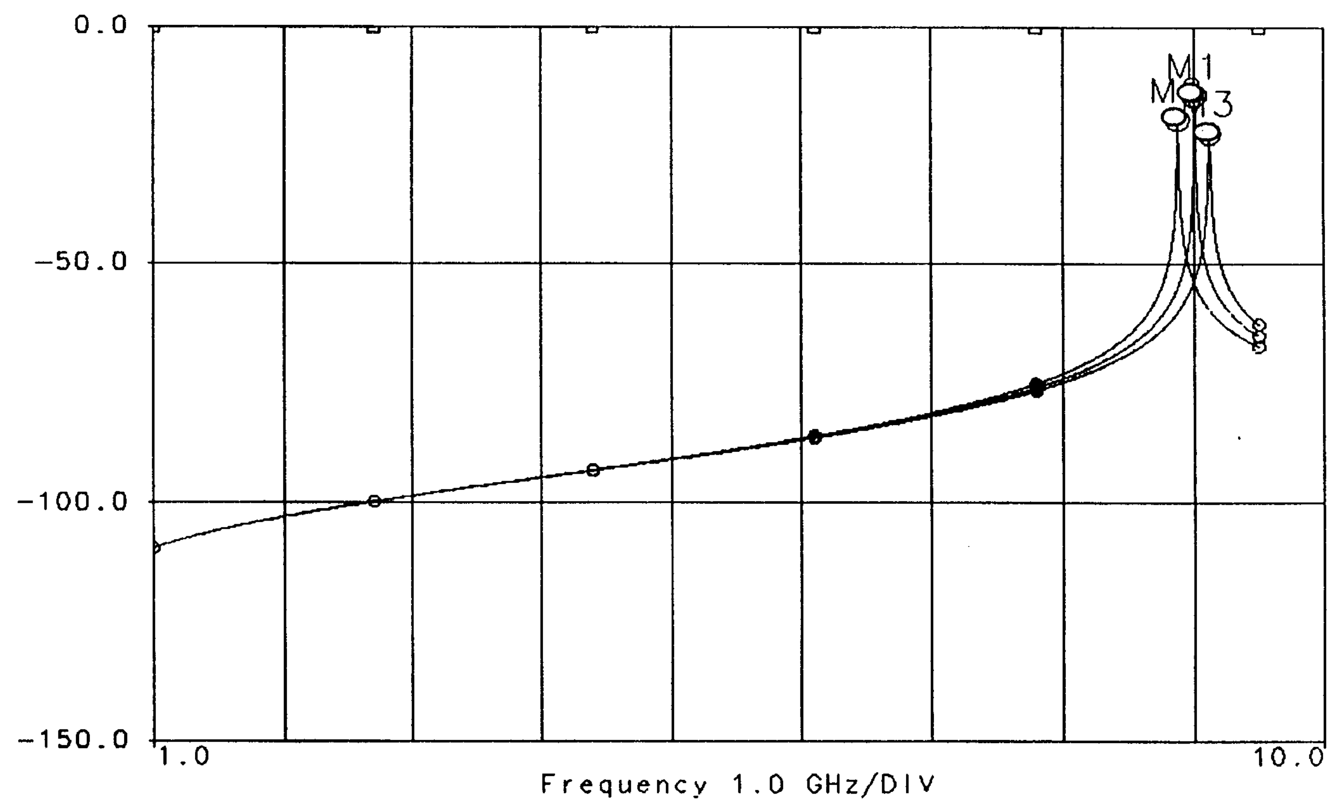
Fabrication Tolerance vs. Tuning

□EMF_Test_tb
SMAT1
EMR_w_Slots
S[1,1]
dB

○EMF_Test_tb
SMAT1
EMR_w_Slots
S[2,1]
dB

Post Gap
Tolerance



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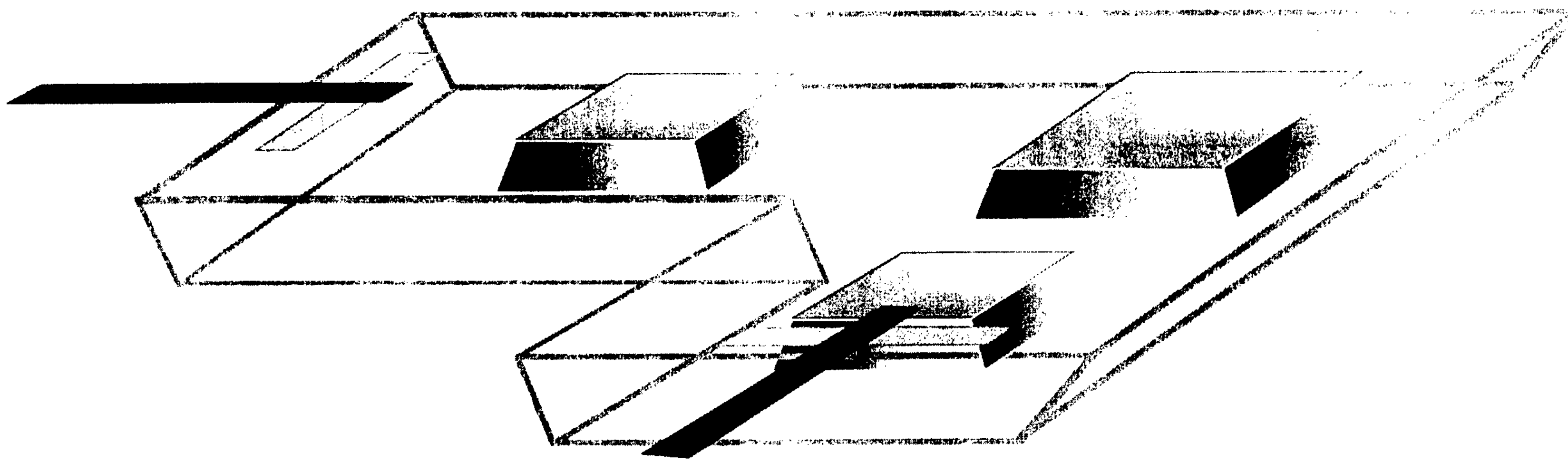
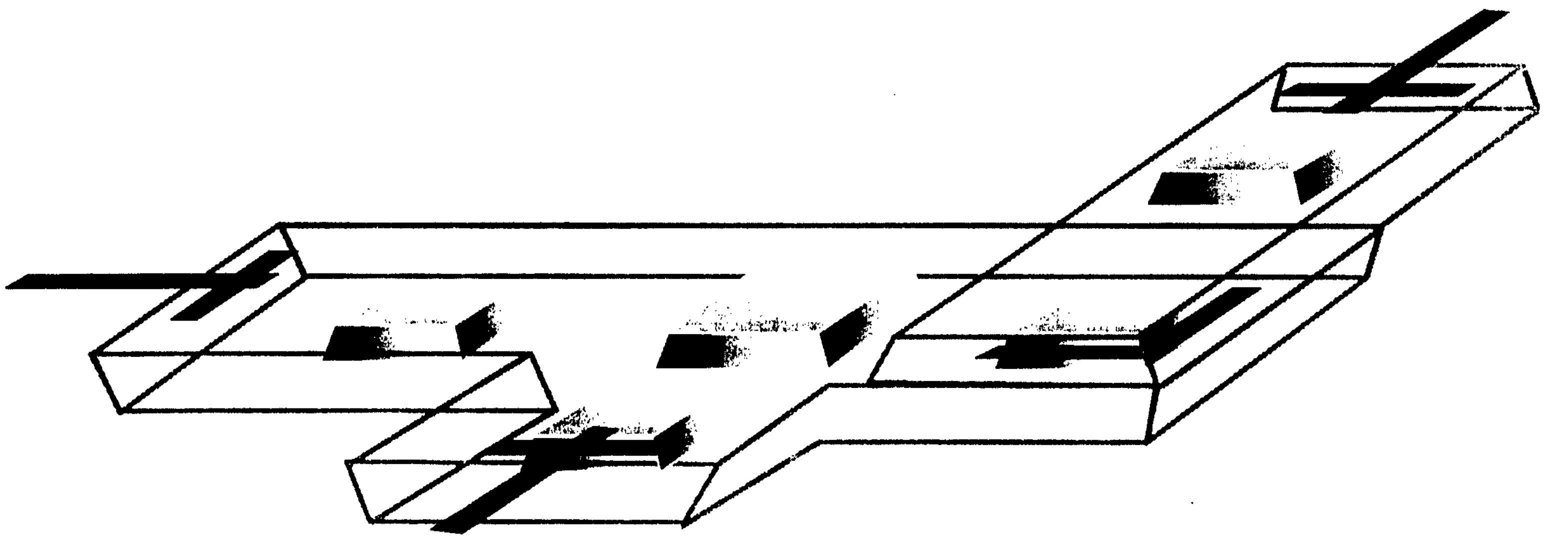
Three Pole Filter

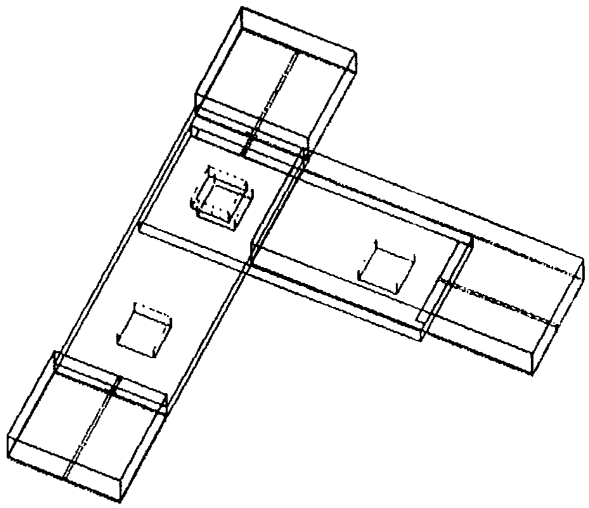


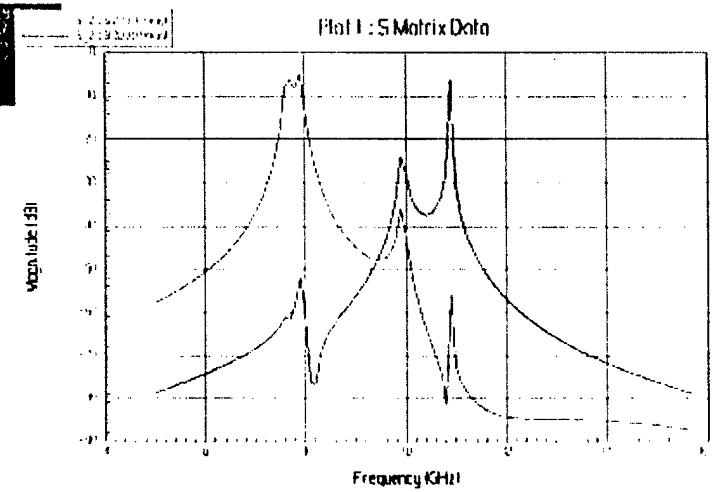
University of

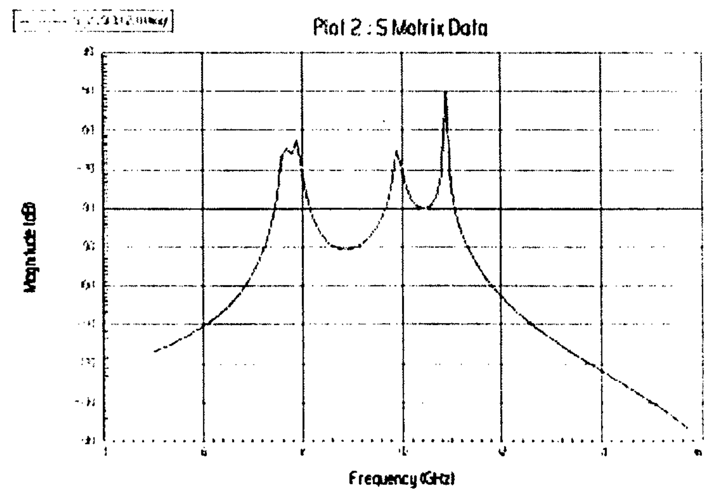
Diplexer



University of







Diplexer Possibility

University of

Accomplishments Micromachined Evanescent Mode Filters

Development of a Design Process for multi-pole filters
Theoretical Simulation of a multipole filter using full-wave techniques to verify method
Successful comparison to LIBRA
Demonstration of a single pole evanescent mode filter with 3% bandwidth and Q approximately 400

March 05 - March 11

March 2001

S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

April 2001

S	M	T	W	T	F	S
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

Monday, March 05

Linda -Dani needs website (Japan)
Linda out of the office Japan

1:30pm 3:00pm Dean's Cabinet (2267 LEC)
3:00pm 4:00pm Assoc. Deans w/Steve (2267 LEC)
4:00pm 5:00pm Saeed
5:30pm 6:30pm Kamal,Dimitrios,Linda
6:30pm 7:30pm Sergio, Jongming, Clark

Tuesday, March 06

Linda -Dani needs website (Japan)
Linda out until 12:00noon

9:30am 11:30am Faculty Candidates
3:15pm 5:00pm CoE Chairs Mtg (2210 LEC)
4:00pm 5:00pm kelly (EECS)
5:00pm 6:00pm Jongming
6:00pm 7:00pm Kok-Yan Lee
7:00pm 7:45pm Eray

Wednesday, March 07

Linda -Dani needs website (Japan)
Steve - out of the office

9:00am 11:00am Executive Committee (2267 LEC)
12:00pm 7:30pm GOMAC-Linda to San ANtonio for this afternoon
4:00pm 5:00pm Parallelization
5:00pm 6:00pm Jim, Jack, Yonkshil, Phil
6:30pm 7:30pm Bill Chappell and Matt Little

Thursday, March 08

Steve - out of the office

8:30am 9:30am Judith Pitney - standing
9:30am 11:30am Faculty Candidates
11:00am 11:30am Multi.Dept Collobration in High Peformance Sci Computing (2210 LEC)
11:30am 12:00pm Ed Borbely - standing mtg
12:30pm 1:30pm NAME Faculty Mtg (232 NAME)
2:30pm 3:00pm Paul - standing
3:00pm 3:30pm Wayne - standing
3:30pm 4:00pm Jim Bean - standing
6:00pm 7:00pm Alex

Friday, March 09

Steve - out of the office (until 3:30)

8:30am 9:30am Faculty Candidates
10:00am 12:00pm APADG (MI League, Henderson)
2:00pm 3:00pm John Halloran - standing (3062B HH Dow)
4:00pm 5:00pm John W./Kyoung/Ron
5:00pm 6:00pm Pallab Bhattacharya/JPL
6:00pm 7:00pm Kostas

Saturday, March 10

2:30pm 3:30pm Donghoon

Sunday, March 11