Transmission Lines for High-Speed/High Frequency Integrated Circuits

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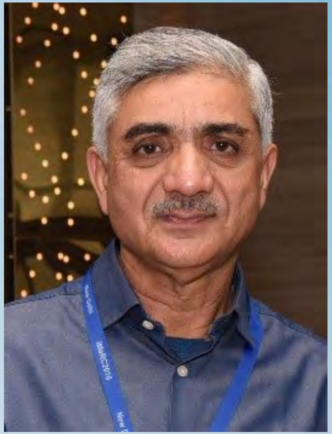


2012-2014 IEEE MTT-S Distinguished Lecturer

2024-2025 IEEE EMC-S Distinguished Lecturer

Brief Contents

- What is EMI, EMC, SI and PI
- Equivalent Circuit of Interconnect Transmission Line
- Conventional Planar Transmission Lines
- Coplanar Transmission Lines
- Variants of Microstrip Transmission Lines
- Suspended Substrate Transmission Lines
- Micromachined Transmission Lines
- Non-Radiative Dielectric Guide Transmission Lines
- Spoof Surface Plasmon Polariton Transmission Lines
- Conventional and High Frequency Interfaces
- Some EMI suppression Techniques
- Novel Circuit Component/Subsystem Development using Transmission Lines

Electronic Circuit Development- Past, Present and Future

Past

- PCB designs were simple due to less population of components and lower frequency of operation.
- All functionalities of a Microcontroller (MCU) could be realized using a single chip with power supply and decoupling capacitors integrated.
- EMI problems needed more attention that SI .

Present and Future

- With IOT revolution, applications have become physically smaller and complex.
- Need interfaces between MCU's and external memories.
- Need to study effect of high data rates on the interfaces.
- Transmission Line effects give rise to SI and PI issues.

Electromagnetic Interference (EMI)

What is EMI

EMI is the interference caused by an electromagnetic disturbance that affects the performance of a device.
Electromagnetic interference often manifests as undesirable noise and may lead to disrupted function of electrical, electronic, and RF systems.

Types of EMI

Conducted EMI – EMI that flows through wires and is caused by physical contact with the source of EMI.

Common Mode EMI – A high-frequency EMI that flows in the same direction through one or more conductors.

Differential Mode EMI – A low-frequency EMI that flows in an opposite direction through adjacent wires.

Radiated EMI – The most common type of EMI, caused by radiating electromagnetic fields. Common manifestations of radiated EMI include static noise on AM/FM radio receivers and "snow" on TV monitors.

Electromagnetic Compatibility

What is EMC?

EMC is a measure of a device's ability to operate as intended in its shared operating environment while, at the same time, not affecting the ability of other equipment within the same environment to operate as intended.

Electromagnetic compatibility of an electrical, electronic, or RF device has two facets:

The ability to work properly in the presence of electromagnetic radiation.

The ability to not generate additional EMI that affects the operation of other devices in its vicinity

- To Meet the System Requirements
- EMC Problems Can Sometimes Have Hazardous Consequences
  - USS Forrestal
  - HMS Sheffield

Signal Integrity (SI)

What is SI?

Signal integrity (SI) is the quality of an electrical signal as it passes through a printed circuit board (PCB). It's a measure of how much the signal degrades from the driver to the receiver.

The Problem is not a major concern at lower frequencies, but it is an important factor when a PCB is operated at a higher Speed and higher frequencies.

Signal distortion takes place due to:

- Signal Characteristics: Ideally a square wave but practically takes some time to rise- signal distortion
- Interconnect Effects: Introduces delays and changes amplitude of signal –jitter and amplitude noise
- Impedance mismatch: Causes reflections- vias and PCB traces, line stubs etc.
- Reflections: Outgoing signals bounce back and interferes with the transmitting pulses
- Cross talk: Rapid voltage and current transitions induce voltages in adjacent traces due to L &C
- Propagation Delay: Signals that travel different distances or through different media do not arrive at same time resulting in signal skew.
- Attenuation: Due to resistance of the traces and board dissipation factor. Effect more noticeable at high frequency due to skin effect
- Ground bounce: Due to ground resistance and interconnect resistance, circuit ground reference level changes resulting in different voltage at different ground locations.
- EMI: Switching operation creates some noise which gets radiated by the traces acting as antennas

Power Integrity (PI)

What is PI?

Power integrity (PI) in a printed circuit board (PCB) is the practice of ensuring that the board's power delivery network (PDN) can distribute power to all components without significant loss or distortion:

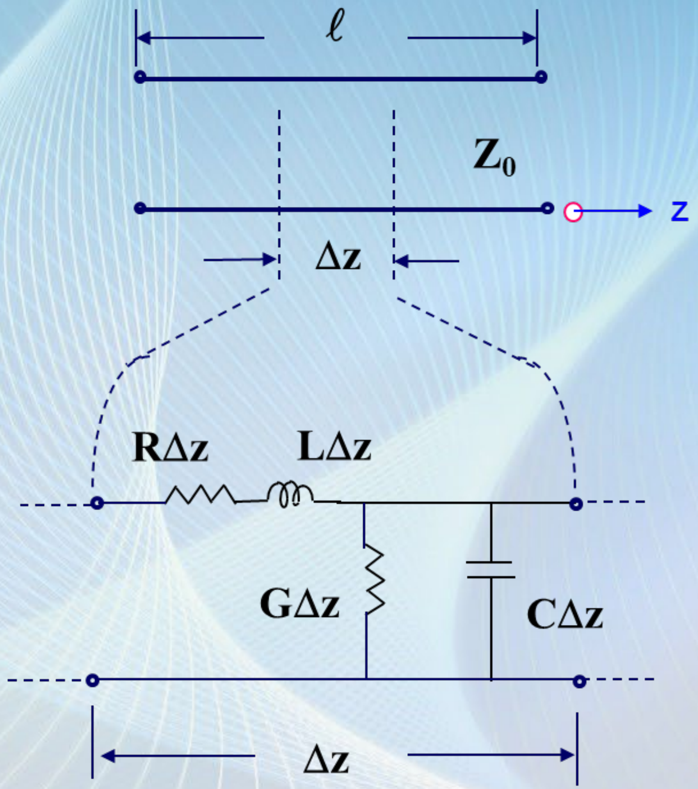
- ❑ Stable voltage: The PDN should provide a consistent voltage level to all components
- ❑ Clean return path: The PDN should provide a continuous return path for high-speed signals to minimize disruption
- ❑ No interference: The PDN should prevent interference between signals

A poorly-designed PDN can lead to unpredictable performance and EMI issues.

Factors affecting Power Integrity:

- ❑ Switched mode power supplies: These can create current transients when converting from AC to DC.
- ❑ Electromagnetic interference (EMI): This can be caused by an unfiltered AC power source
- ❑ DC power loss and heat: The amount of DC power lost as heat is proportional to the current squared

Interconnect line of ℓ in a System (ℓ comparable to λ)



Equivalent circuit model

$\Delta z <<< \lambda$

R : resistance/unit length (Ω/m)

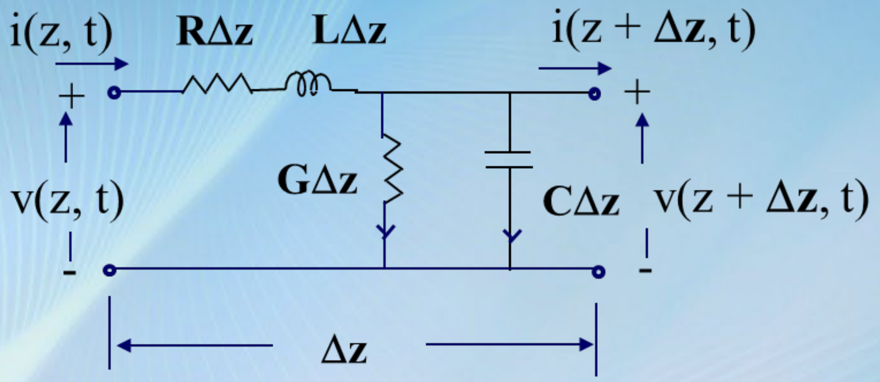
L : inductance/unit length (H/m)

G : conductance/unit length (℧ /m)

C : capacitance/unit length (F/m)

Transmission Line- Circuit Analysis

Apply KVL and KCL to infinitesimal section of TL



KVL ⇒ $$v(z,t) - R\Delta z\, i(z,t) - L\Delta z \frac{\partial i(z,t)}{\partial t} - v(z+\Delta z,t) = 0$$

KCL ⇒ $$i(z,t) - G\Delta z\; v(z+\Delta z,t) - C\Delta z \frac{\partial v(z+\Delta z,t)}{\partial t} - i(z+\Delta z,t) = 0$$

Transmission Line- Wave Equation

$$\frac{d^2V(z)}{dz^2} = \gamma^2 V(z),$$

$$\frac{d^2I(z)}{dz^2} = \gamma^2 I(z)$$

$$V(z) = V_0^+ e^{-\gamma z} + V_0^- e^{\gamma z}$$

$$I(z) = I_0^+ e^{-\gamma z} + I_0^- e^{\gamma z}$$

$e^{-\gamma z}$: wave travelling in the $+z$ direction

$e^{\gamma z}$: wave travelling in the $-z$ direction

Propagation Constant

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

α : Attenuation Constant (Np/m) ; β : Phase Constant (rad/m)

$$Z_0 = \frac{R + j\omega L}{\gamma} = \frac{\gamma}{G + j\omega C} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (\Omega)$$

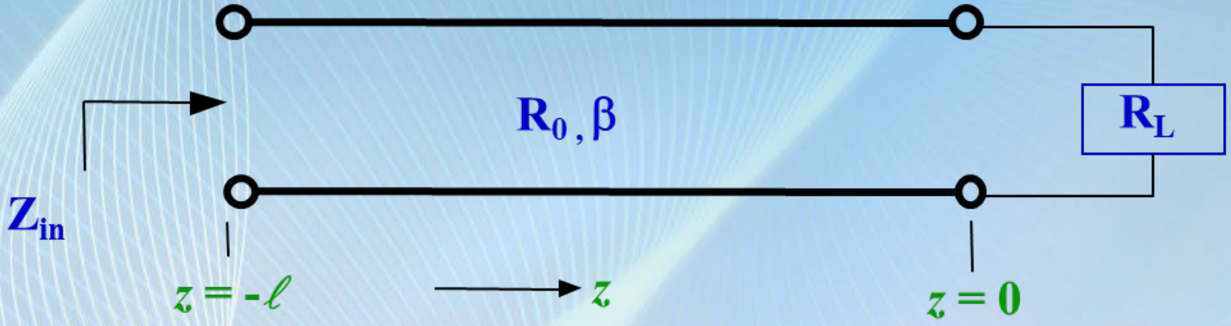
Transmission Line- Limiting Cases

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (m^{-1})$$

Distortion less $R/L = G/C$ **ensures that different frequency components in the signal suffer same attenuation and they also travel with the same velocity.**

Dispersion : **A general lossy line has phase constant which is not a linear function of frequency: Different frequency components of the signal propagate along the line with different velocities, the overall signal suffers dispersion.**

Terminated Transmission Line



$$\Gamma = \frac{R_L - R_0}{R_L + R_0}$$

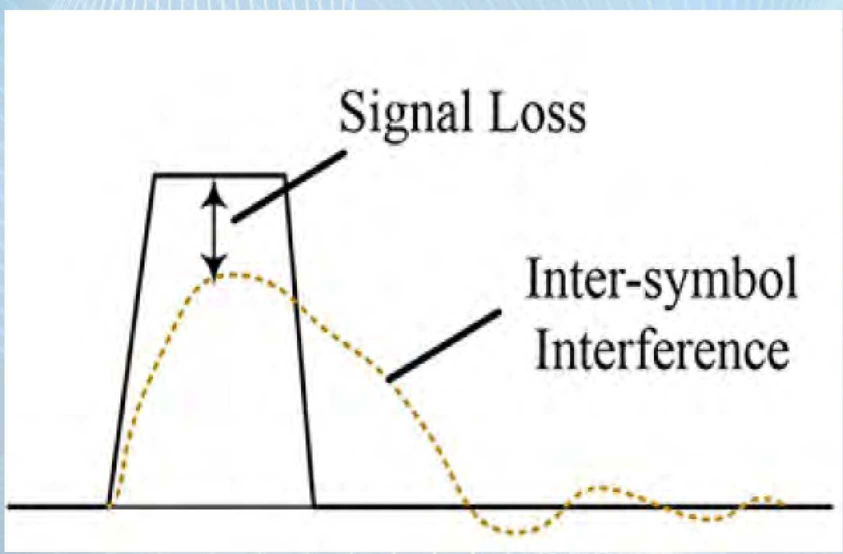
$R_L = R_0$; Γ is Zero

$R_L > R_0$; Γ is Positive

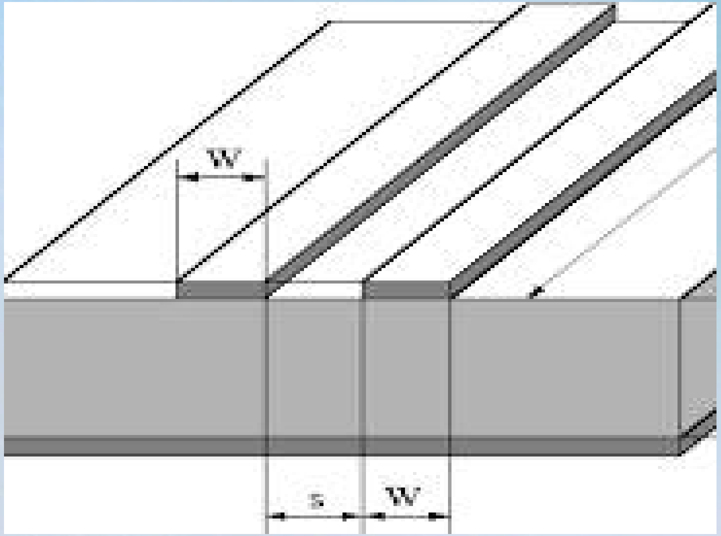
$R_L < R_0$; Γ is negative

Most Common Failure Modes

Signal Integrity Issues due to interfaces and high data rates



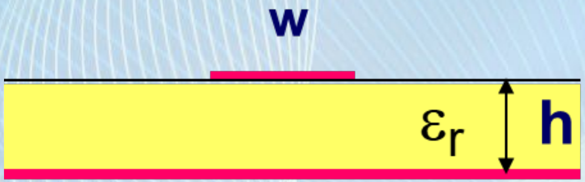
EMI issues due to Radiation and Cross Talk



Conventional Transmission Lines

Stripline

Shorter Traces than microstrip, Produces less crosstalk and Lower EMI radiations



Microstrip

Easier to fabricate, Produces more crosstalk and more EMI radiations at discontinuities

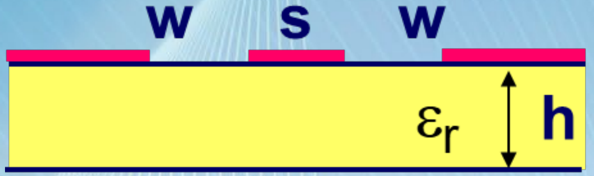
Embedded Microstrip

Trace better protected from exposure to environment

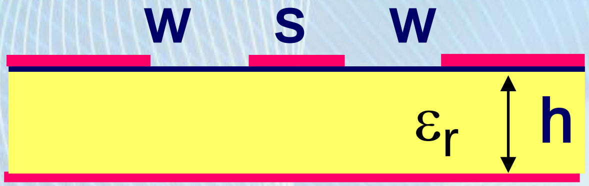
Higher density of components and interfaces due to narrower trace width (approximately 30% lower)

EMI radiation better than Microstrip

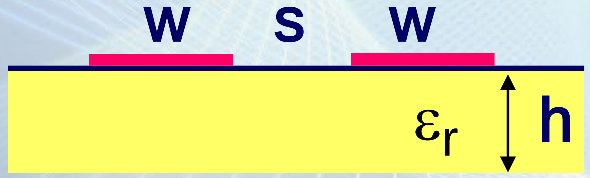
Coplanar Transmission Lines



Coplanar Waveguide



Grounded Coplanar Waveguide



Coplanar Strips

Basic Coplanar Waveguide has signal line in the centre and semi-infinite grounds on both sides. S=0 is a Slot Line

Direct integration of high frequency active and passive components

Slight reduction in radiation loss compared with microstrip

Wider effective bandwidth compared with microstrip

Less impedance variations as a function of frequency

Grounded Coplanar waveguide connects the top ground to the bottom ground using vias to suppress higher order modes

Better isolation and lower radiation losses due to bottom ground plane.

In general routing density increases using grounded coplanar waveguide

Variants of Microstrip Line

Suspended Microstrip

Reduction in effective permittivity, convenient circuit dimensions at mm Wave frequencies, isolation improvement by adjusting airgap

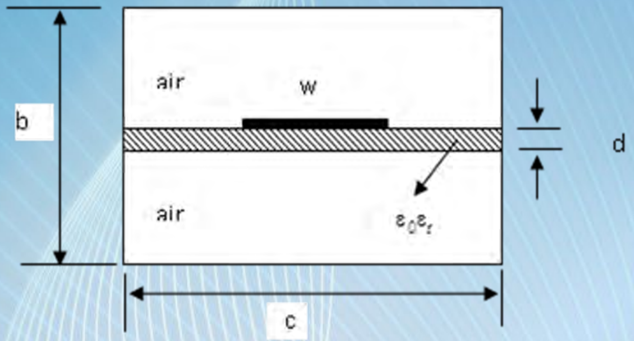
Inverted Microstrip

Effective Permittivity Close to 1, Trace better protected from exposure to environment, Less EMI radiation at discontinuities

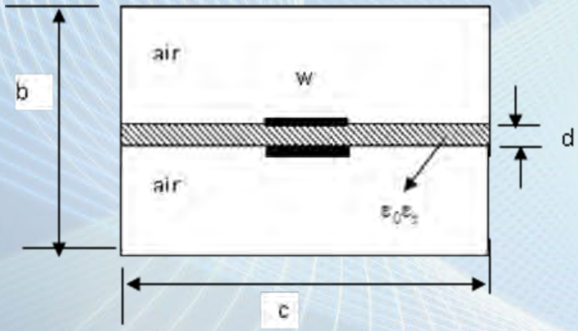
Trapped Inverted Microstrip

Trace better protected from exposure to environment, As the fields are trapped in the channel, less EMI radiation at discontinuities, High isolation easily achieved.

Suspended Substrate Line



Suspended Substrate Line (SSL)



Broadside Coupled SSL

Dielectric Substrate suspended in metallic Enclosure-Effective Permittivity=1

Traces can be printed on both sides of the substrate

Thin Dielectrics with low permittivity usually preferred

Wide range of Impedance values typically up to 300 ohms possible

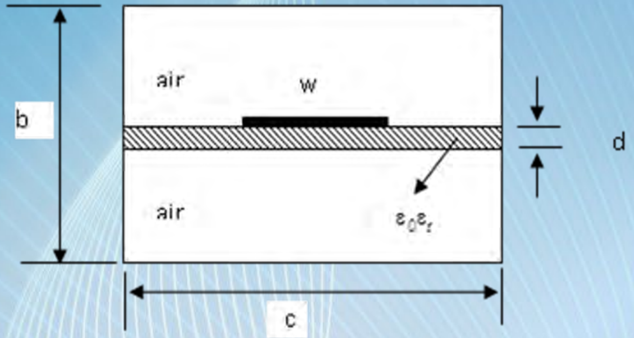
No EMI Radiation as the structure is fully shielded

Since most of the field is in air, losses are considerably reduced resulting in high Q circuits- typical Q is of the order of 500.

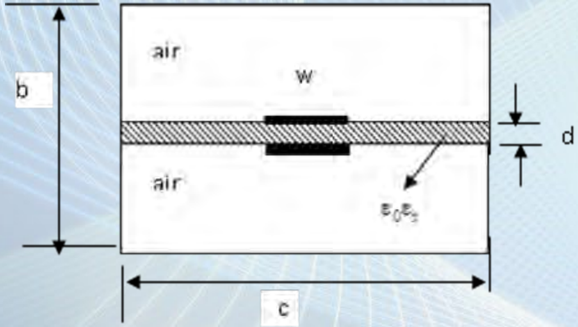
SSL suitable for circuits that need to withstand vibration and shock and operate over wide temperature range from -55^0 to 70^{0}C.

SSL Useful up to 300 GHz

Advantages of Suspended Substrate Line



Suspended Substrate Line (SSL)



Broadside Coupled SSL

Low Loss; Reduces signal attenuation due to air and low loss dielectrics

High Isolation; Excellent shielding from the ground plane reduces cross talk and EMI

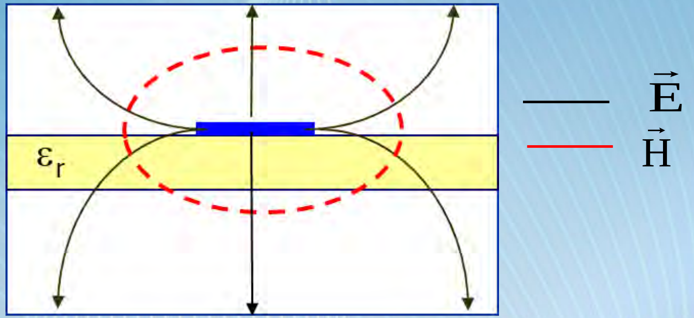
Improved Dispersion: The suspended design reduces signal distortion and dispersion.

Applications include:

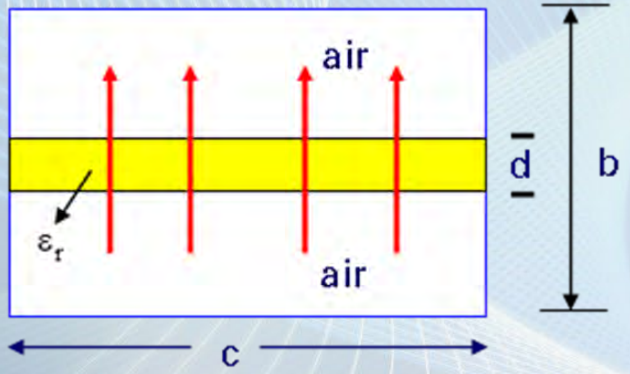
- **Microwave and Millimeter Wave circuits**
- **High speed digital systems**
- **RF and microwave amplifiers**
- **Antenna Feed Networks**

Suspended strip lines are commonly used in high frequency designs where signal integrity and minimal loss are crucial.

Suspended Substrate Line Channel Dimensions



Dominant TEM Mode in (SSL)



Higher Order TE_{10} Mode in SSL

To ensure only dominant mode propagation, we need to select channel dimensions c and b appropriately.

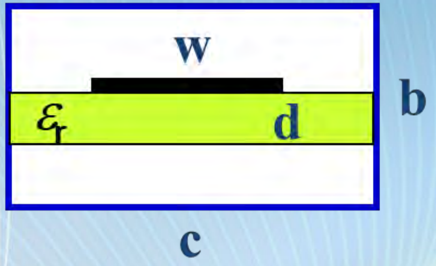
Choose channel dimensions such that cutoff frequency of TE_{10} (LSM) mode is above the highest frequency of operation of the SSL circuit.

Useful to built circuits up to 300 GHz easily

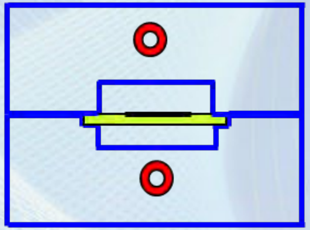
$$f_{c(LSM)} = \frac{v_o}{2c}\sqrt{1-\frac{d}{b}\left(1-\frac{1}{\varepsilon_r}\right)}$$

If d=0.254 mm, $\varepsilon_r = 2.22$, selecting c=2.35 mm and b=1.2 mm will ensure dominant mode operation up to 60 GHz.

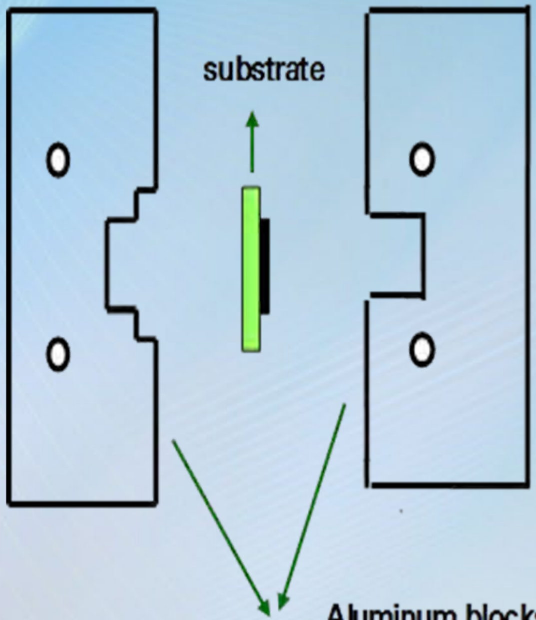
Suspended Substrate Line Housing Construction



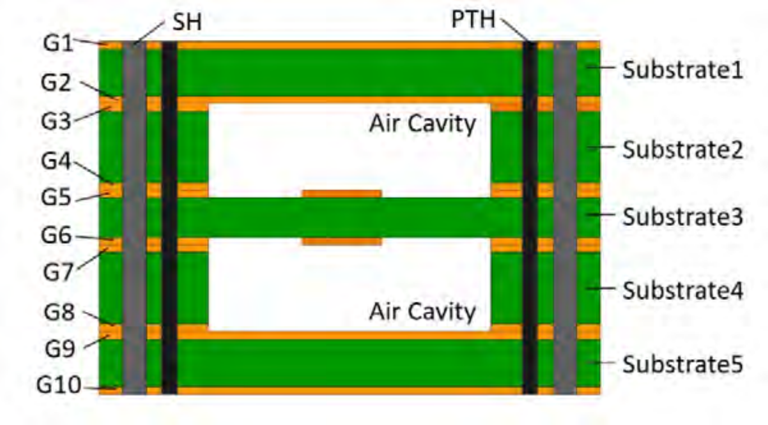
Suspended Stripline

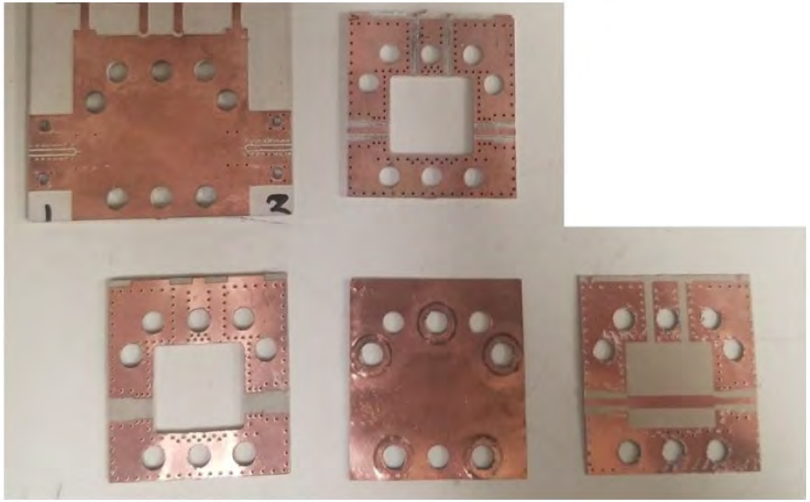


SSL Housing construction



Substrate Integrated Suspended Substrate Line (SISL)





SISL uses 5 substrates and 10 ground metallic layers
Rivets used to hold substrates in position (SH)
PTH for forming SSL Cavity
Useful for fabricating SMT Components
Components and sub-systems up to sub-Terahertz communication feasible

Fabricated SISL SMT through Line

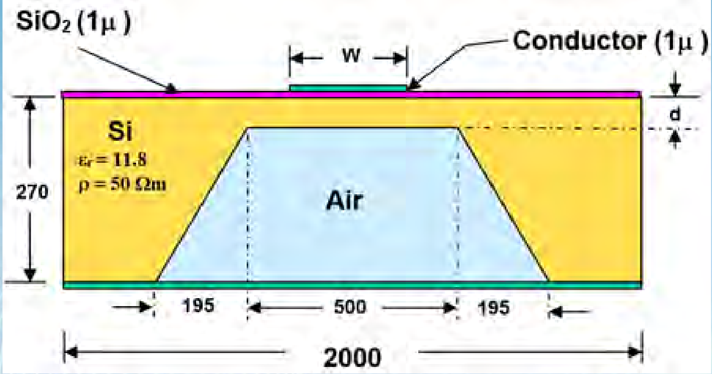
Source: IEEE Trans. On MTT, Vol.67, No.3, March 2019

Source: IEEE Trans. On Components and Packaging, Vol.13, No.7, July 2023

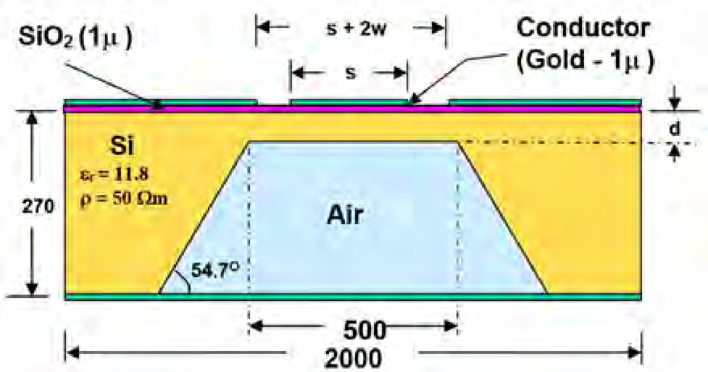
Signal Integrity Improvement using SISL

- **Reducing Signal loss**: By suspending the substrate signal attenuation is minimized, allowing signal to travel farther without degradation.
- **Shielding**: The insulating layers surrounding the substrate act as a shield , reducing EMI and cross talk between the signals.
- **Improved Impedance Matching**: SISL's controlled impedance environment ensures better matching between components reducing signal reflections and distortion.
- **Reduced Parasitic Capacitance**: SISL minimizes parasitic capacitance which can distort signals and reduce bandwidth.
- **Improved Signal Isolation**: The insulating layers and suspended substrate reduces signal coupling and noise, improving SNR.
- **Enhanced Thermal Management**: SISL helps reduce thermal noise and signal degradation due to temperature fluctuations.
- **Reduced Radiation Losses**: The shielding layers minimize radiation losses, hence reducing energy losses.

Micromachined Transmission Lines



Micromachined Microstrip



Micromachined Coplanar Waveguide

Both Micromachined microstrip and coplanar waveguides are fabricated using Bulk Micromachining

Effective permittivity of these structures is close to 1 although the base substrate is Si.

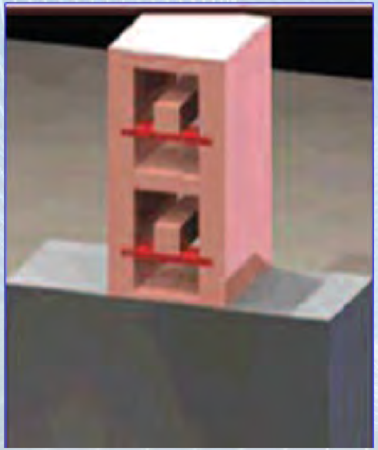
Losses are considerably lower as compared with conventional microstrip and coplanar waveguides

Wide range of Impedance values possible because of air cavity

Circuit dimensions especially at millimetre wave frequencies are at least 3-4 times larger than conventional microstrip

Due to air cavity high Q circuits possible.

Polystrata@R Technology



New Enabling Architecture for future 3D Millimeter Wave Circuits

Perfectly shielded, low loss, pure TEM broadband transmission line

20X smaller than conventional coax lines

85X smaller separation between lines for same isolation as compared with PCBs

Suitable for products in the 10-200 GHz range

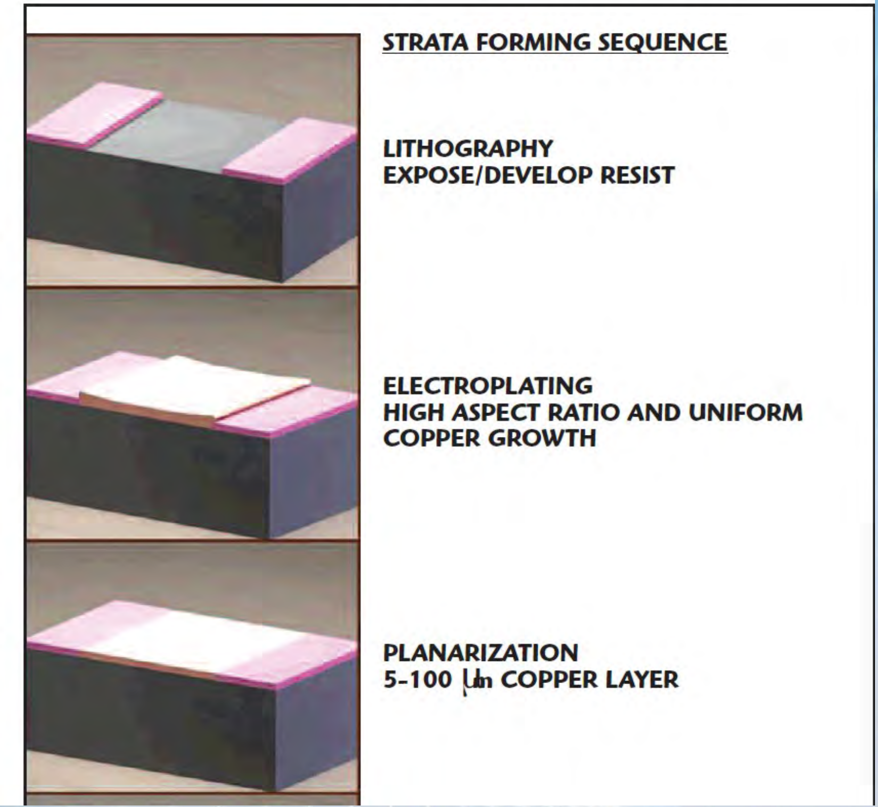
Ultra low dispersion

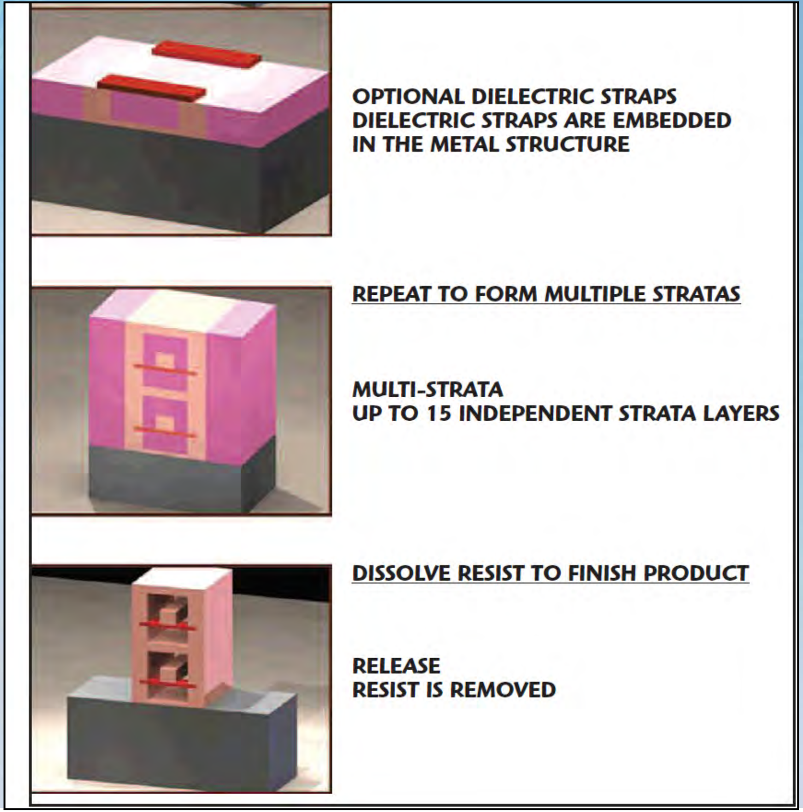
Very low loss per wavelength

Extremely high isolation and very low radiations from the circuits enabling highly dense interconnects

Source: Microwave Journal, February 2008 issue

Polystrata@R Fabrication Process

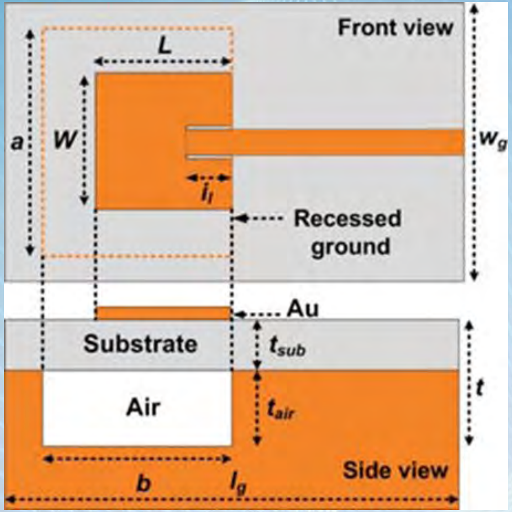


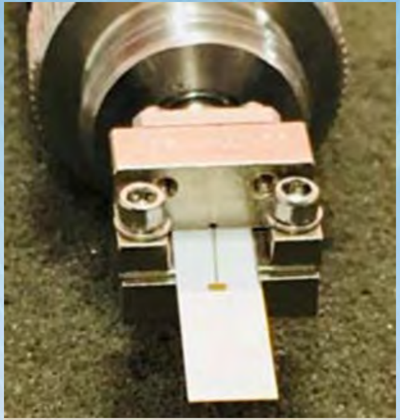


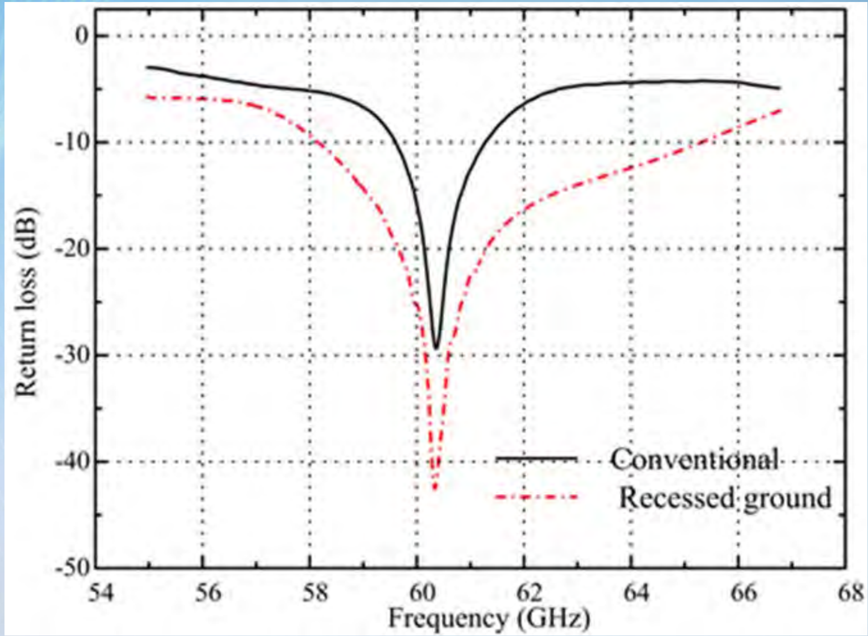
Patented by Nuvotronics and Cubic Corporation

Source: Microwave Journal, February 2008 issue

Recessed Ground Transmission Lines

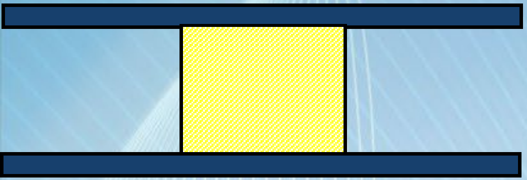


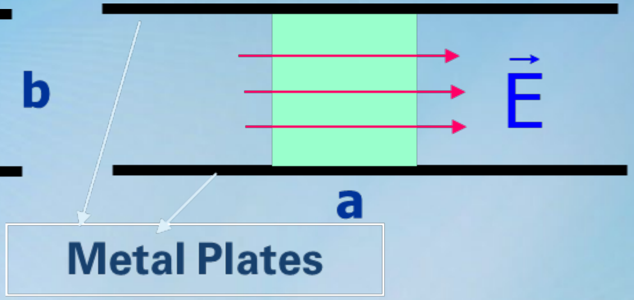




- Source: Anushruti, Mahesh and Shiban K Koul, IEEE Transaction on AP, Vol.67, No.4, April 2019

Non-radiative Dielectric Guide Transmission Lines





Principle of Operation of NRD Guide

- 26-100 GHz
- Very low loss
- Low Cross Talk
- Low-cost technology
- Low EMI Radiations

$$b < \lambda_0 / 2$$

Fields are cutoff

$$b / \lambda_0 \approx 0.45$$

$$b < \lambda_0 / 2$$

Cutoff is eliminated

$$\left(\frac{a}{\lambda_0}\right)\sqrt{\varepsilon_r - 1} \approx 0.4 - 0.6$$

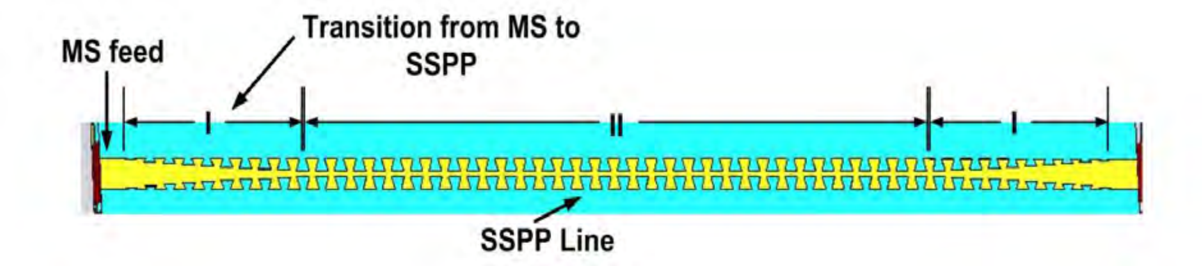
Spoof Surface Plasmon Polariton (SSPP) Transmission Line

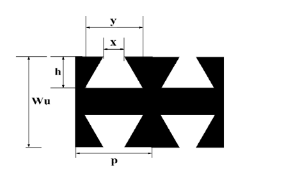
Surface Plasmon Polaritons (SPP) are surface waves that propagate at the interface between dielectrics and metals at optical Frequencies

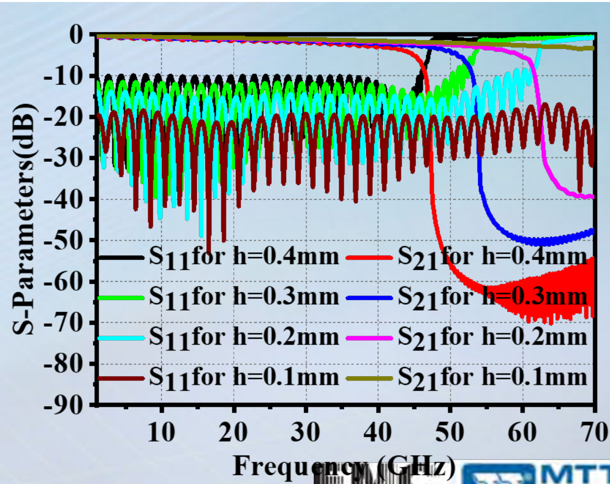
Pendry in 2004 and F.J.Garcia Vidal et al in 2005 analytically proved that by inserting a corrugation of periodicity d , width a and depth of corrugation h shows the property of surface plasmon at lower frequencies hence known as spoof surface plasmon (SSP)

For next generation ultrabroad-band communication SSPP is a perfect candidate

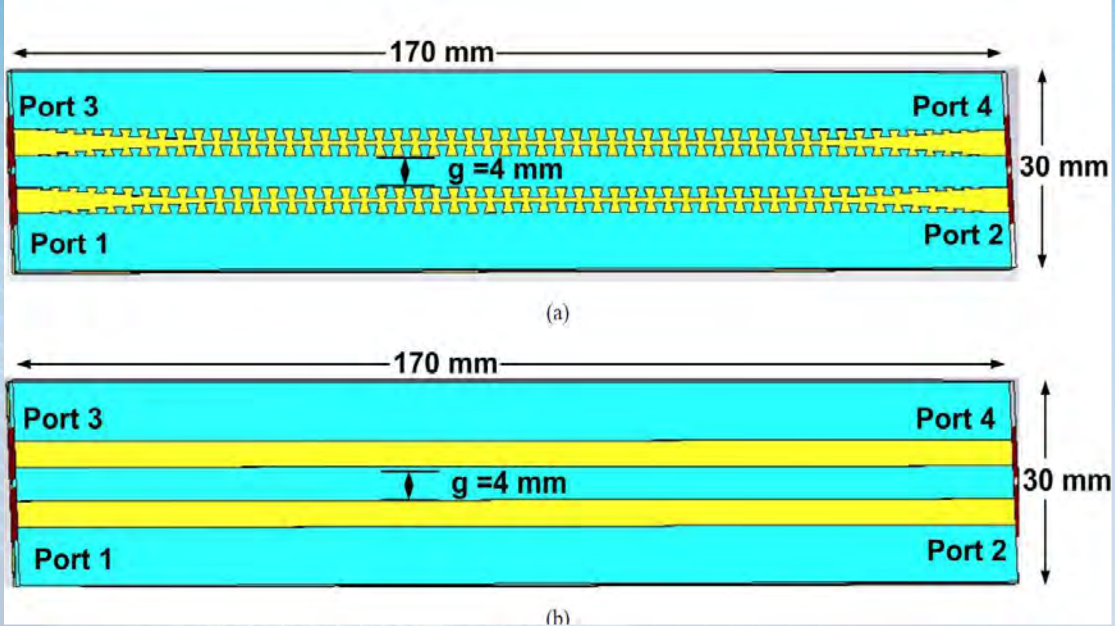
Lower transmission losses, very good isolation, less cross talk and minimum EMI radiation from bends

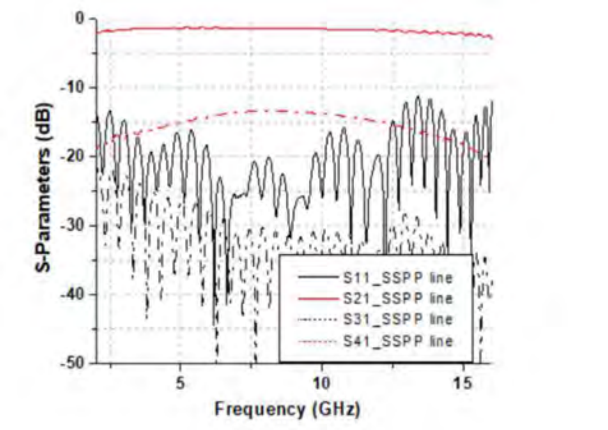


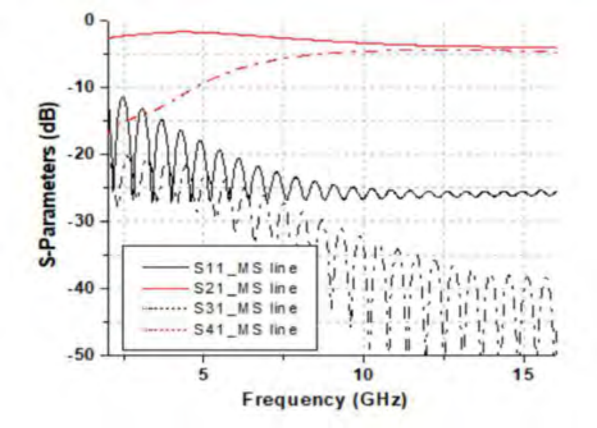




Spoof Surface Plasmon Polariton (SSPP) Transmission Line

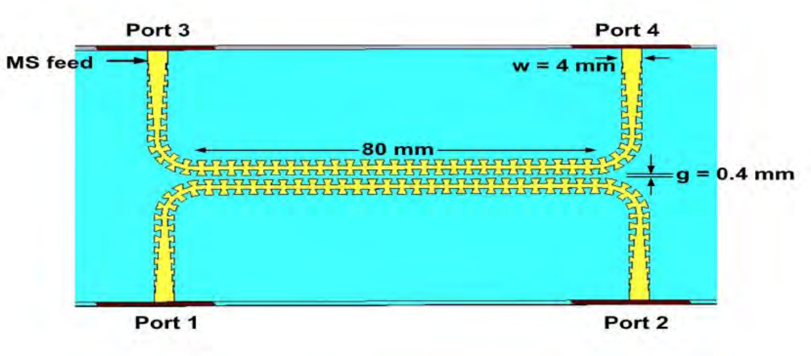




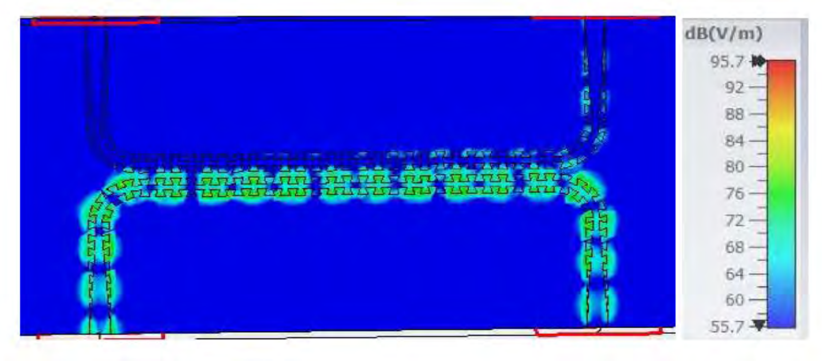


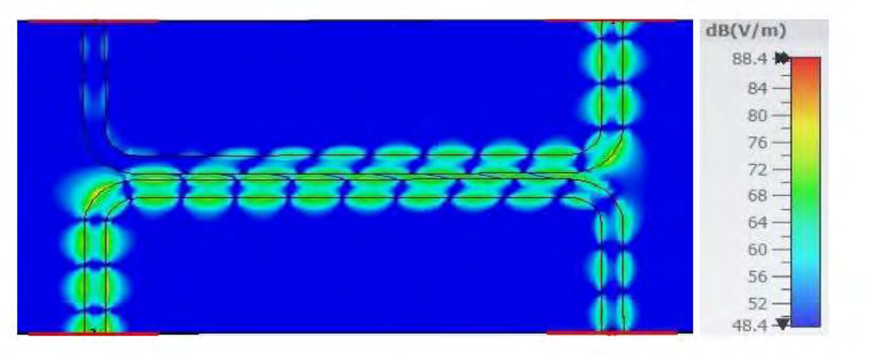
Improved Isolation in SSPP Structure as compared with Microstrip

Spoof Surface Plasmon Polariton (SSPP) Transmission Line



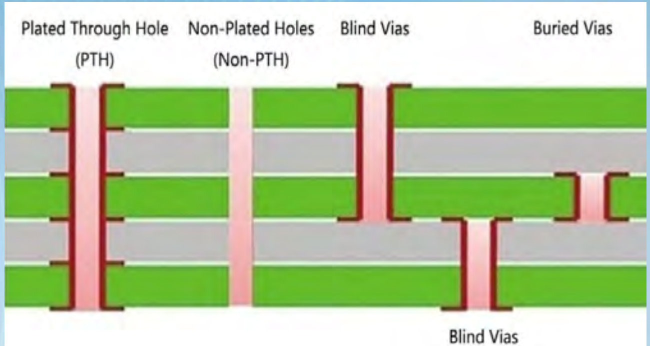
Microwave ICs based on SSPP Lines, Shiban Koul and Somia Sharma, Springer, August 2025



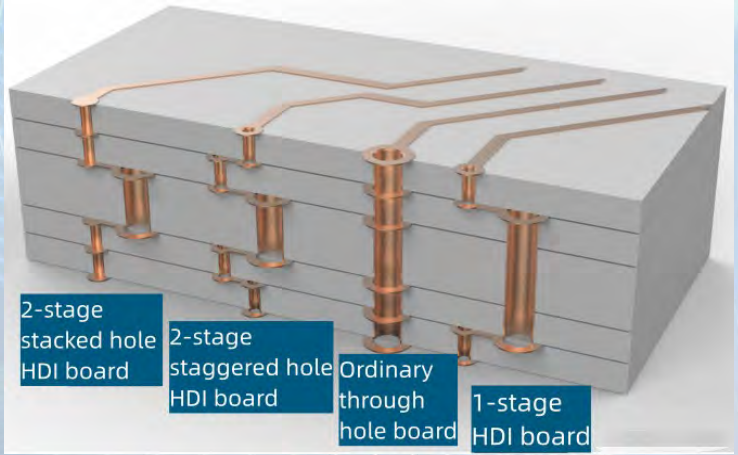


E-field distribution in SSPP Structure as compared with Microstrip

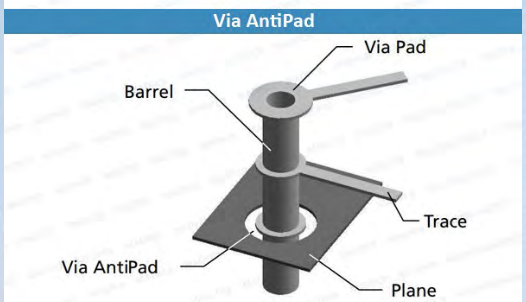
Multi-Layer PCB and Vias

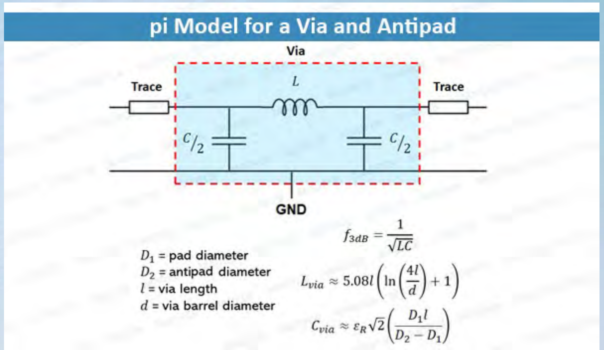


Source: PCBJHY Company



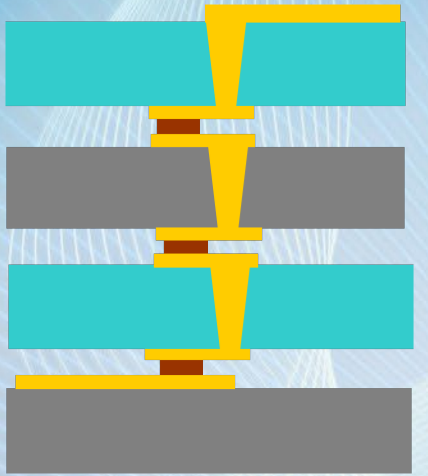
Source: http://yuwpcb.com/news_view.php?id=84



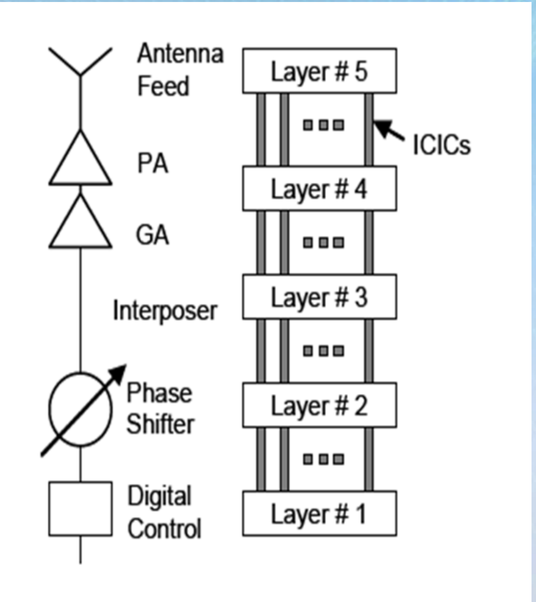


Source: http://madpcb.com/glossary/antipad

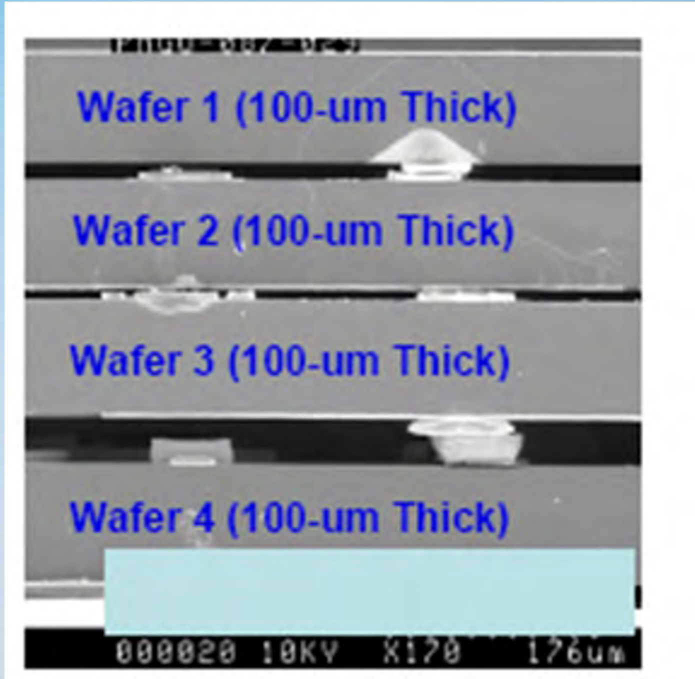
Other High Frequency Interfaces



LTCC-Low Temperature
Co-fired Ceramic Technology

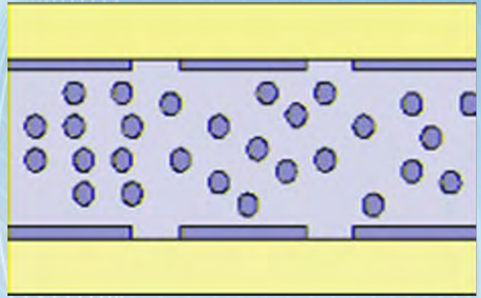


LCP Technology



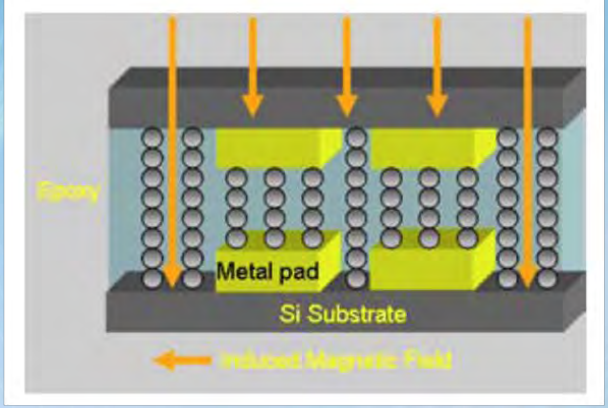
GaAs Wafer Level Stacking Technology

Anisotropic Conductive Adhesive Based High Frequency Interface

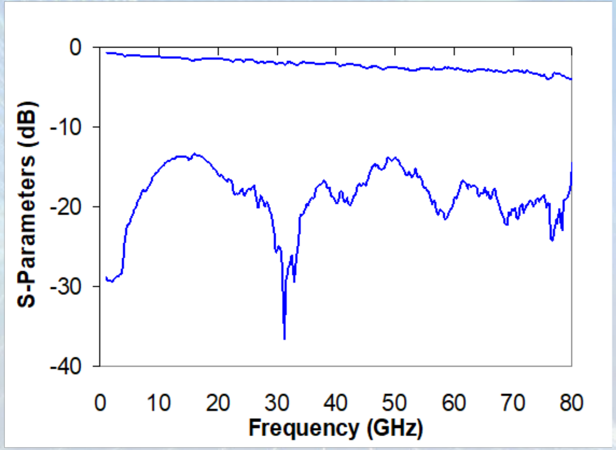


Before Curing

Gold Coated Ferromagnetic Particle



After Curing



Replacement for Flip Chip bonding of devices or wafers at high frequencies

Source: IEEE Transactions on MTT, Nov.2008

Material Based Absorbers

Colloids and Surfaces A: Physicochemical and Engineering Aspects 699 (2024) 134535

Contents lists available at ScienceDirect

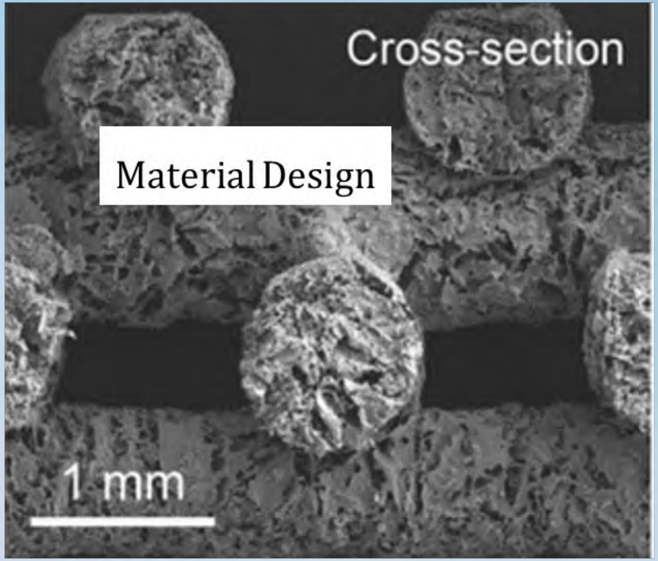
Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

ELSEVIER

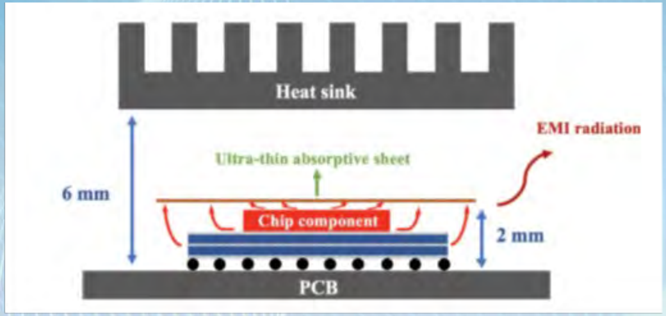
Enhanced EM shielding: Synergetic effect of zirconium ferrite, MWCNT, and graphene in LDPE polymer composite to counteract electromagnetic radiation in the X-band range

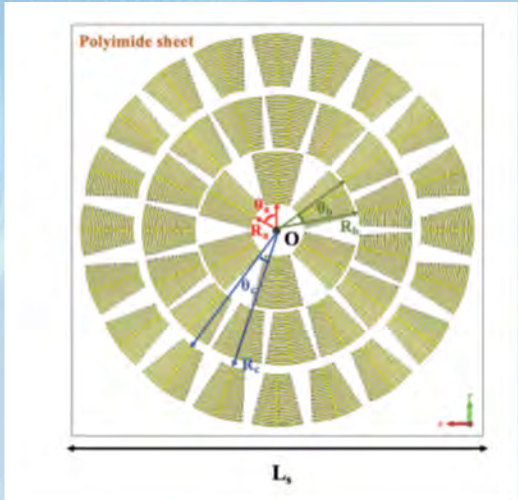
M. Praveen [a,*], B.P. Harichandra [b], R. Hari Krishna [c,d], Mohan Kumar [e,*], G.S. Karthikeya [f], H.R. Swamy [g], Shiban Koul [h], B.M. Nagabhushana [c]

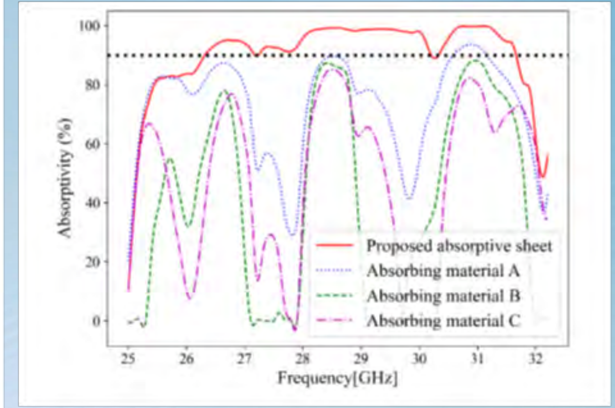


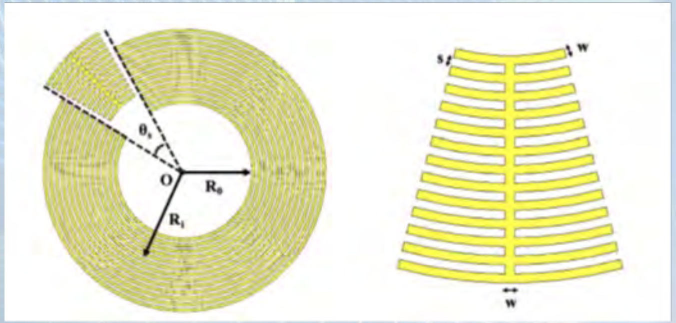
Shi, S., Jiang, Y., Ren, H. *et al.* 3D-Printed Carbon-Based Conformal Electromagnetic Interference Shielding Module for Integrated Electronics. *Nano-Micro Lett.* 16, 85 (2024)

Ultra-Thin SSPP Based sheet for Suppressing Microwave Radiated Emissions in System in Package (SIP) Modules



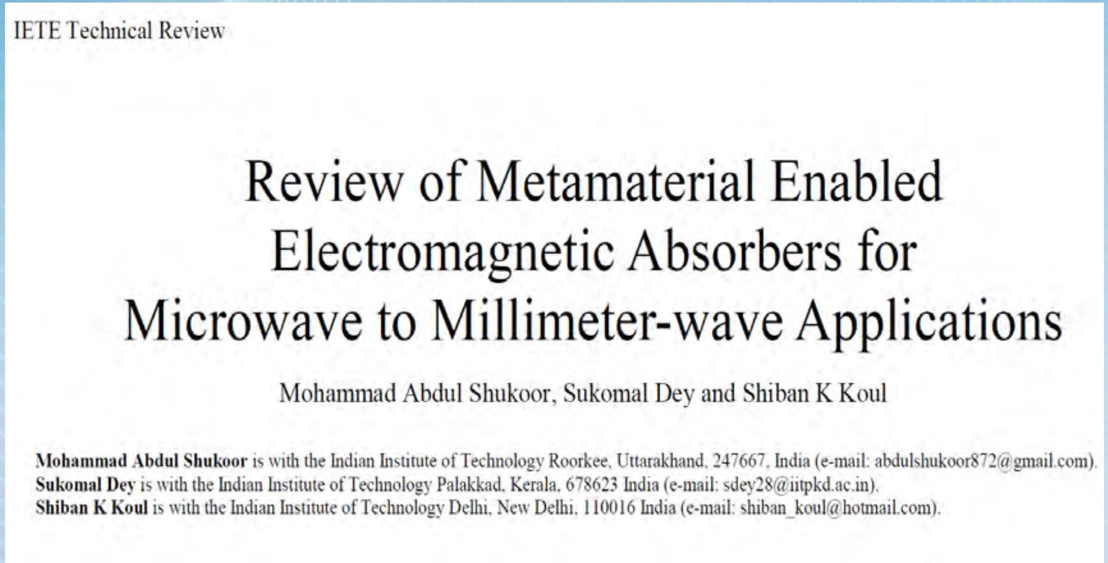






Source: IEEE Transaction on EMC, Vol.65, No.2,pp.376-385, April 2023

PCB Based Absorbers

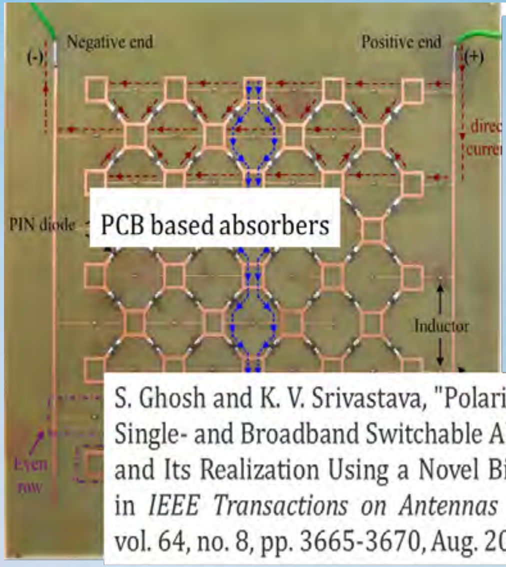


IETE Technical Review

Review of Metamaterial Enabled Electromagnetic Absorbers for Microwave to Millimeter-wave Applications

Mohammad Abdul Shukoor, Sukomal Dey and Shiban K Koul

Mohammad Abdul Shukoor is with the Indian Institute of Technology Roorkee, Uttarakhand, 247667, India (e-mail: abdulshukoor872@gmail.com).
Sukomal Dey is with the Indian Institute of Technology Palakkad, Kerala, 678623 India (e-mail: sdey28@iitpkd.ac.in).
Shiban K Koul is with the Indian Institute of Technology Delhi, New Delhi, 110016 India (e-mail: shiban_koul@hotmail.com).



S. Ghosh and K. V. Srivastava, "Polarization-Insensitive Single- and Broadband Switchable Absorber/Reflector and Its Realization Using a Novel Biasing Technique," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 8, pp. 3665-3670, Aug. 2016

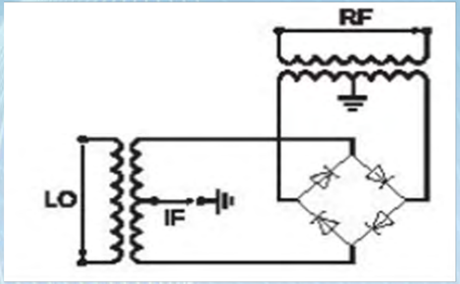
Metamaterial Inspired Multiband Broadband and Reconfigurable Absorbers and Polarization Converters, S.Dey, A.Sukoor and Shiban Koul, Springer, December 2025

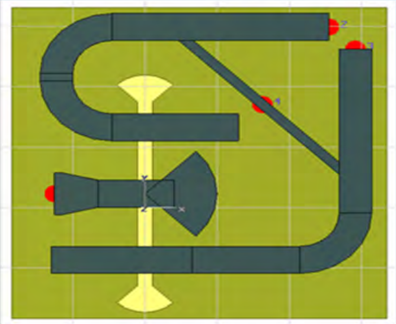
Novel Components/Subsystems utilizing Tx Lines

Double Balanced Mixer using Microstrip Slot-line Junction

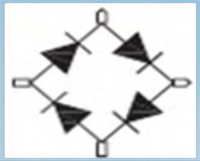
- Example of a 18-40 GHz Mixer

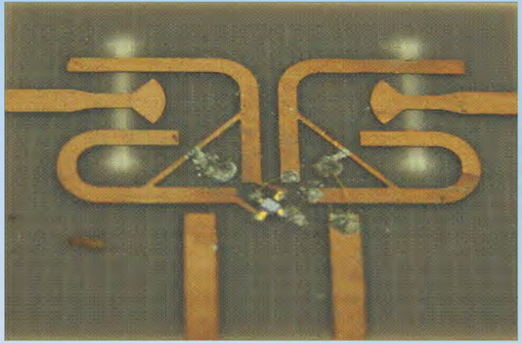
Double balanced Mixer

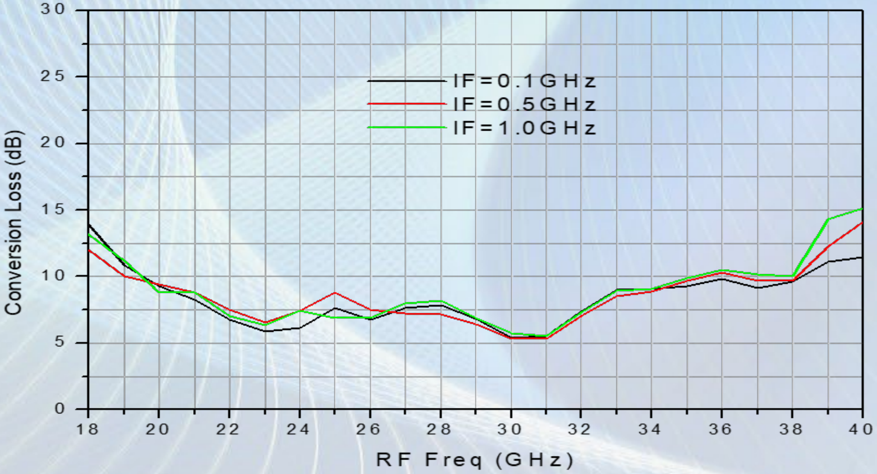




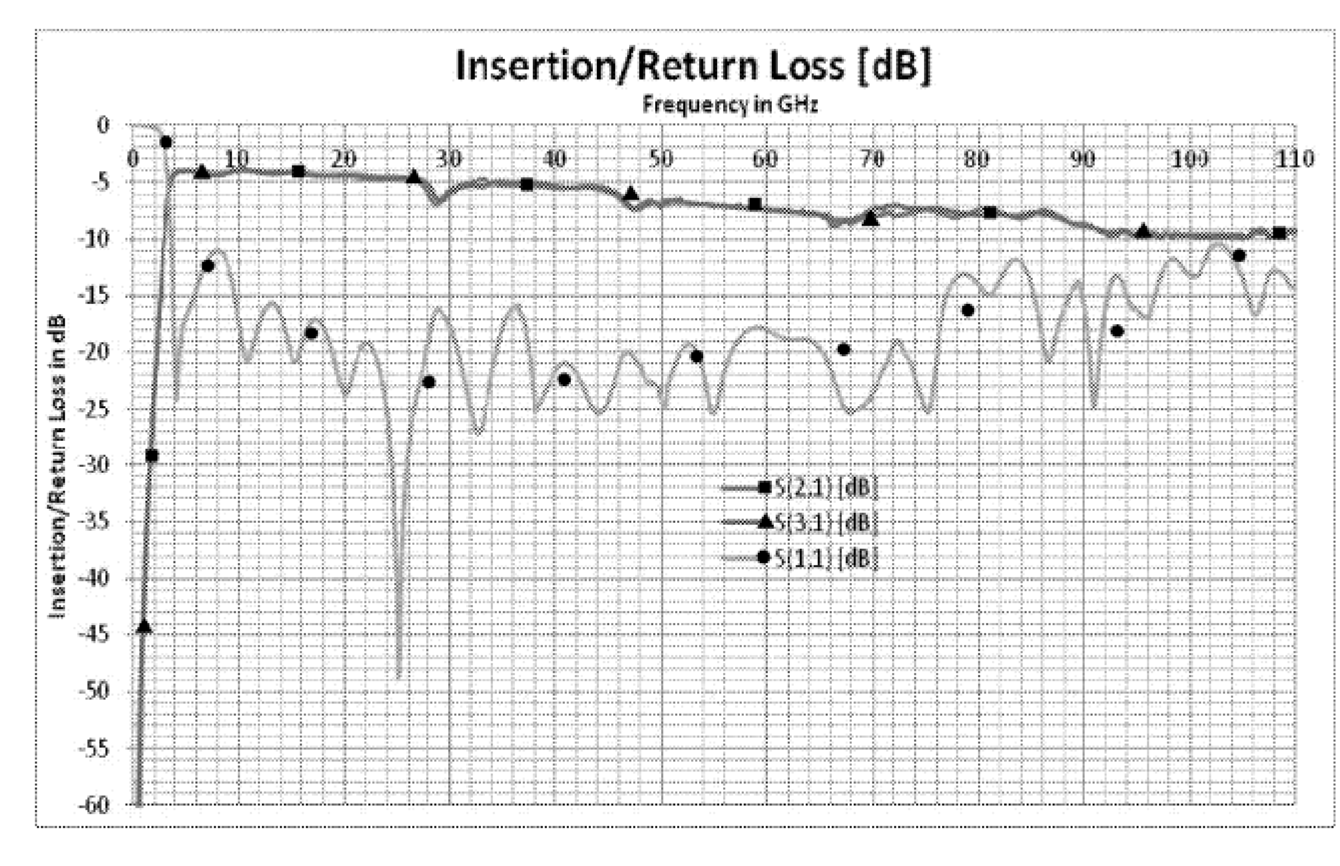
Diode used MSG904





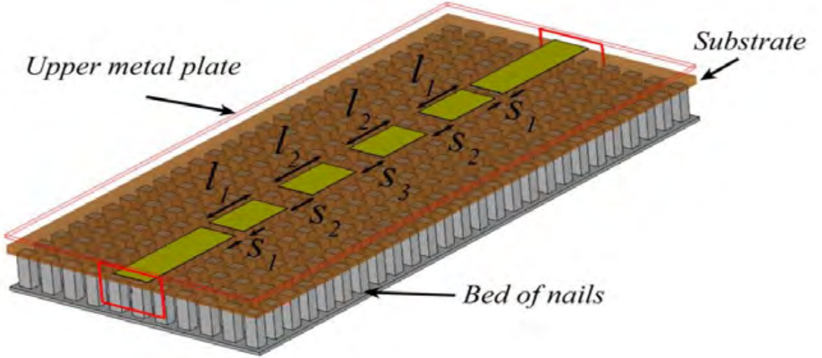


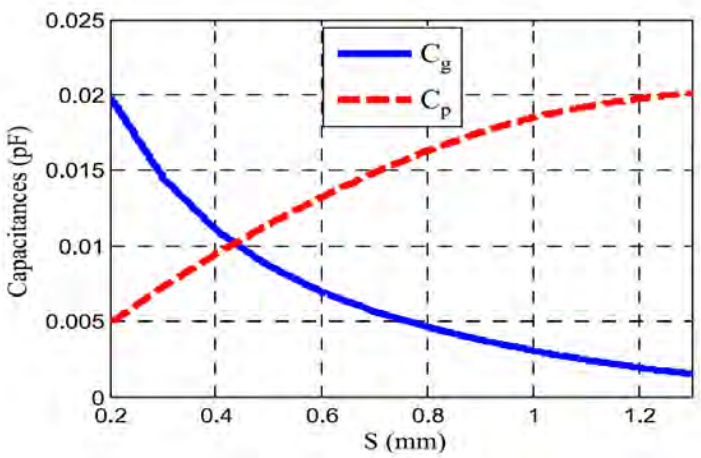
Ultra Broadband Balun using Microstrip Slot-line Junction

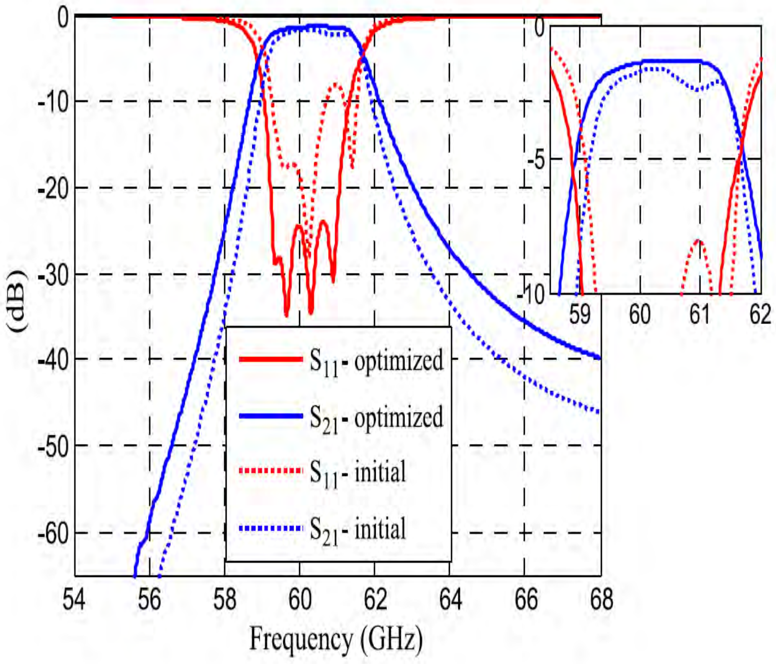


US Patent: US9923257
B2- Granted 08-03-2018

Trapped Inverted Microstrip Bandpass Filter





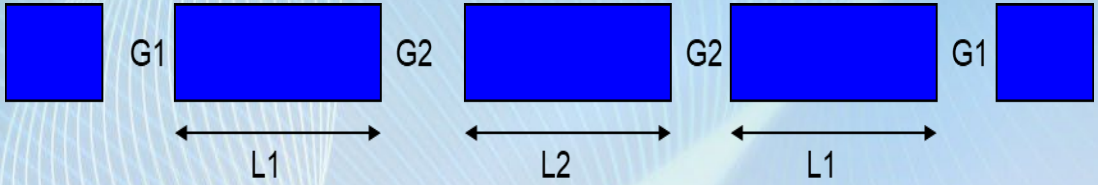


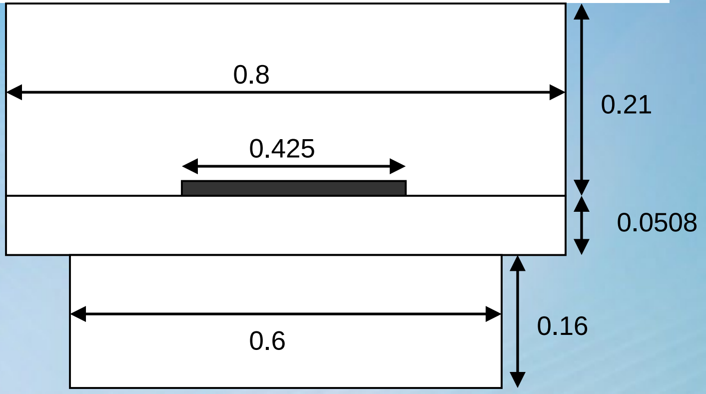
Source: IEEE Microwave and wireless Component Letters, Vol.26,No.4,2016, pp.262

140 GHz Suspended Substrate Line Band Pass Filter

Dielectric Constant = 3.78

N=3, BW= 3 GHz



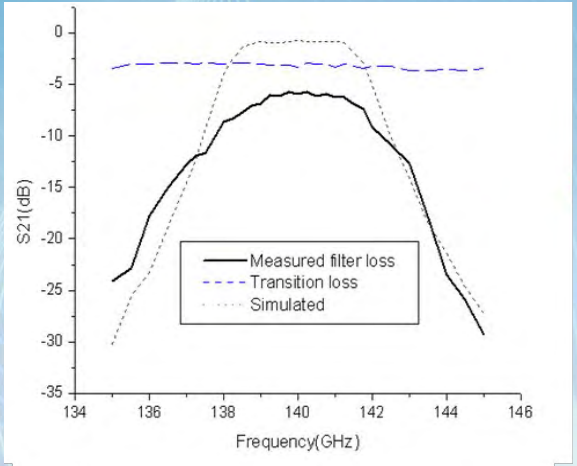


Sr No	J-Inverter	Gap(mm)	S21[mag ang]	S11[mag ang]
1.	0.1806	0.140	0.3465 48.32	0.9353 -41.68
2.	0.0309	0.381	0.06105 52.39	0.9966 -37.91
3.	0.0309	0.381	0.06105 52.39	0.9966 -37.91
4.	0.1806	0.140	0.3465 48.32	0.9353 -41.68

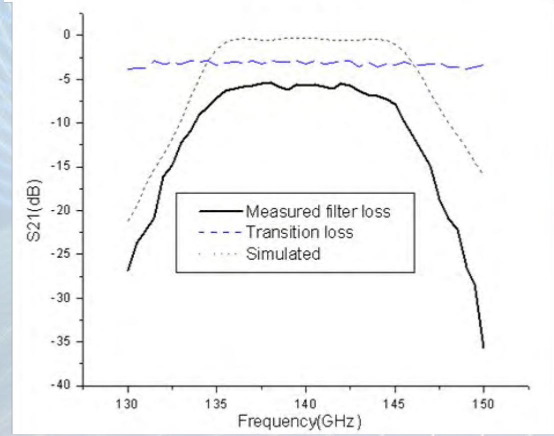
140 GHz Suspended Substrate Line Band Pass Filter

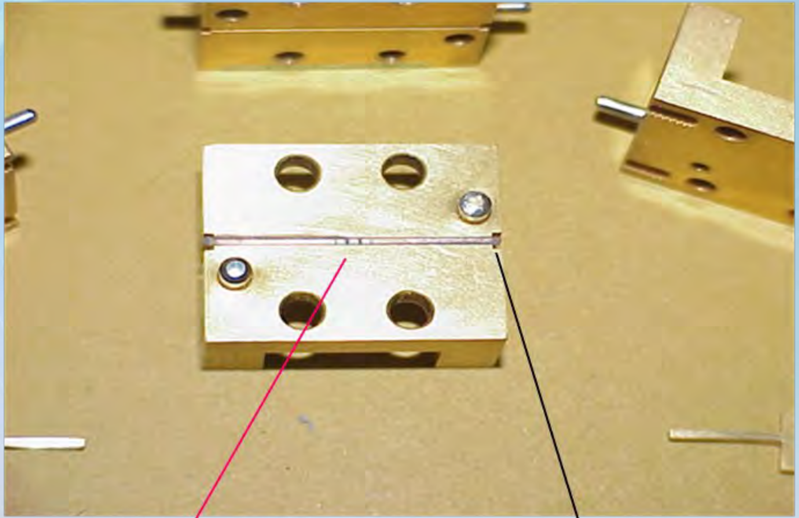
- 140 GHz Band pass Filter Response

BW= 3 GHz



BW= 10 GHz

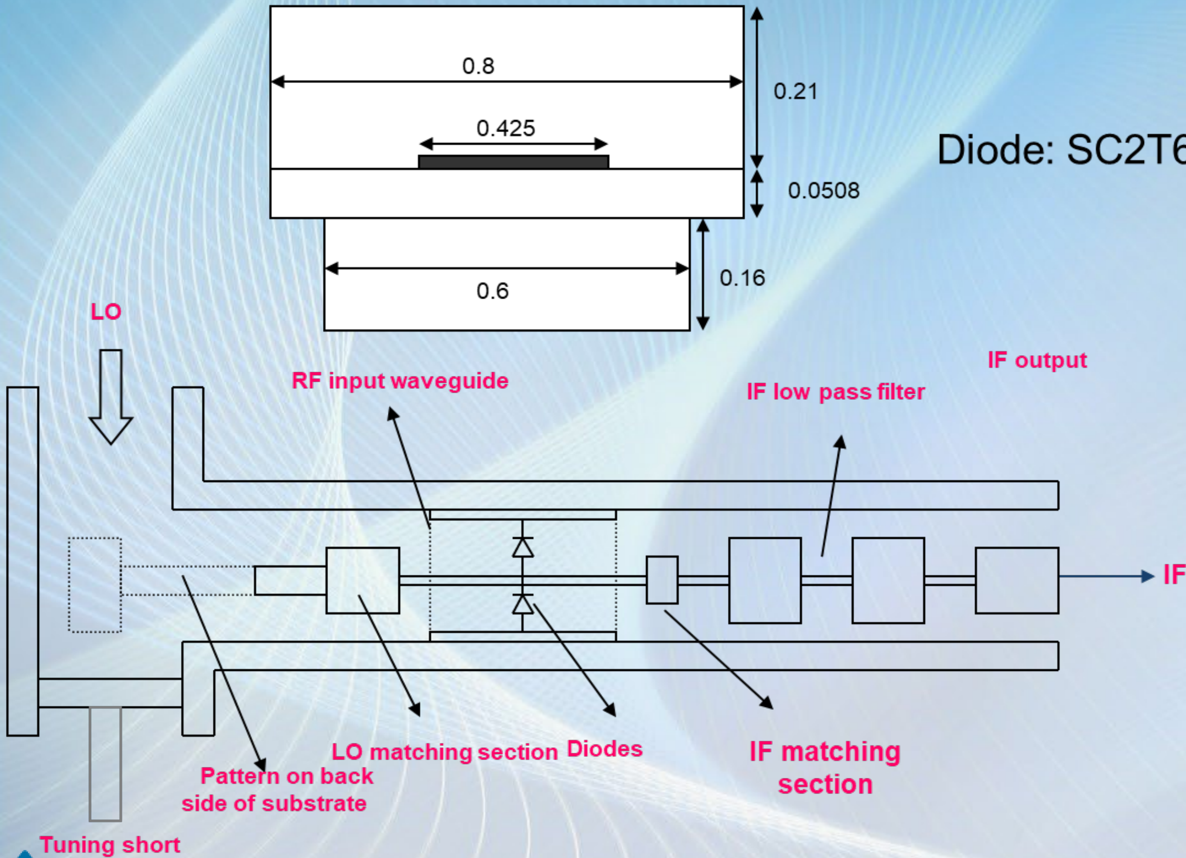




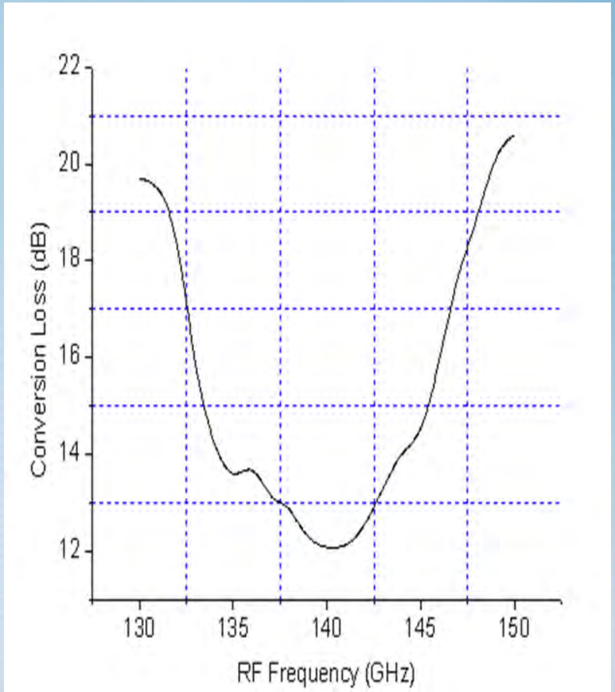
BPF Layout

Transition to waveguide

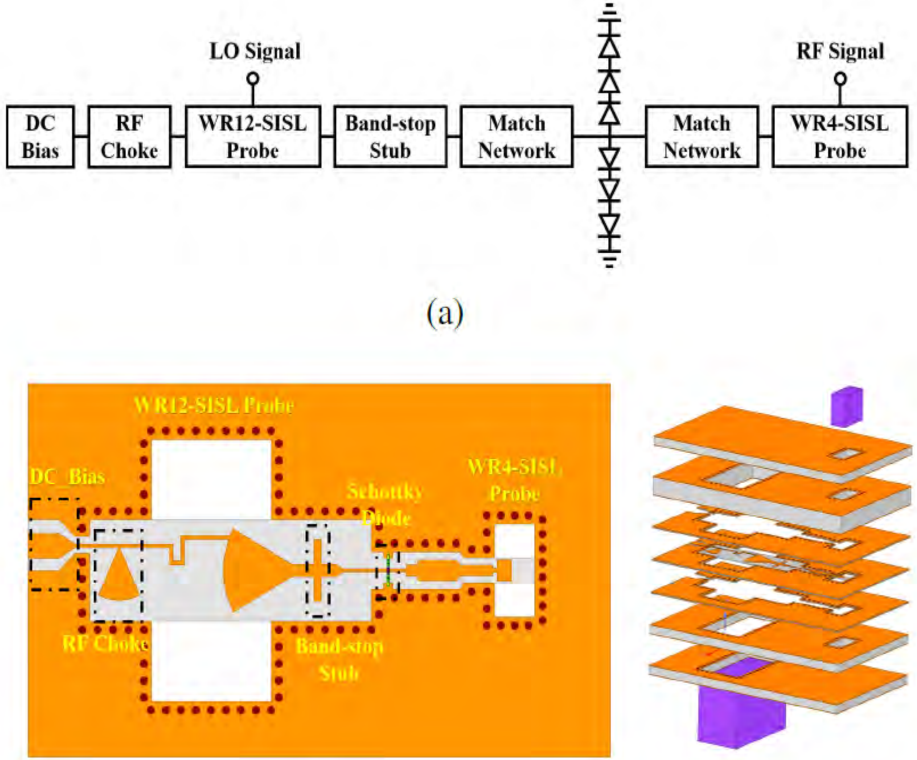
140 GHz Suspended Substrate Line Mixer



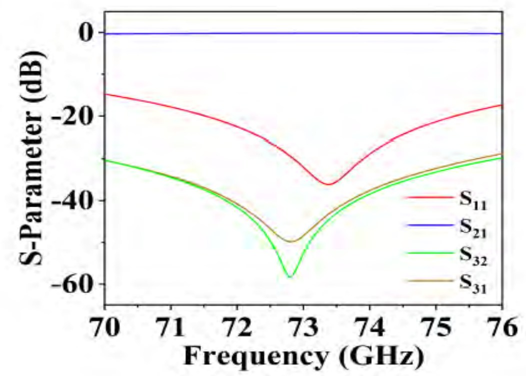
Diode: SC2T6

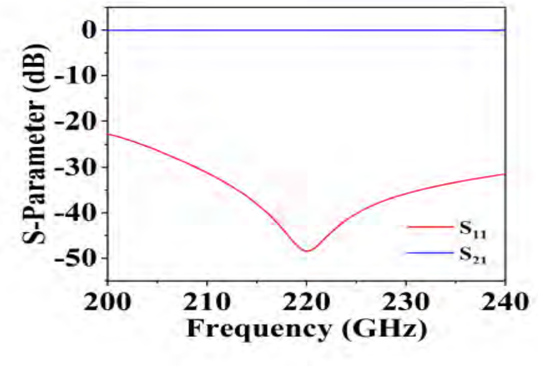


220 GHz Frequency Tripler Based on SISL Platform



(a) (b) (c)

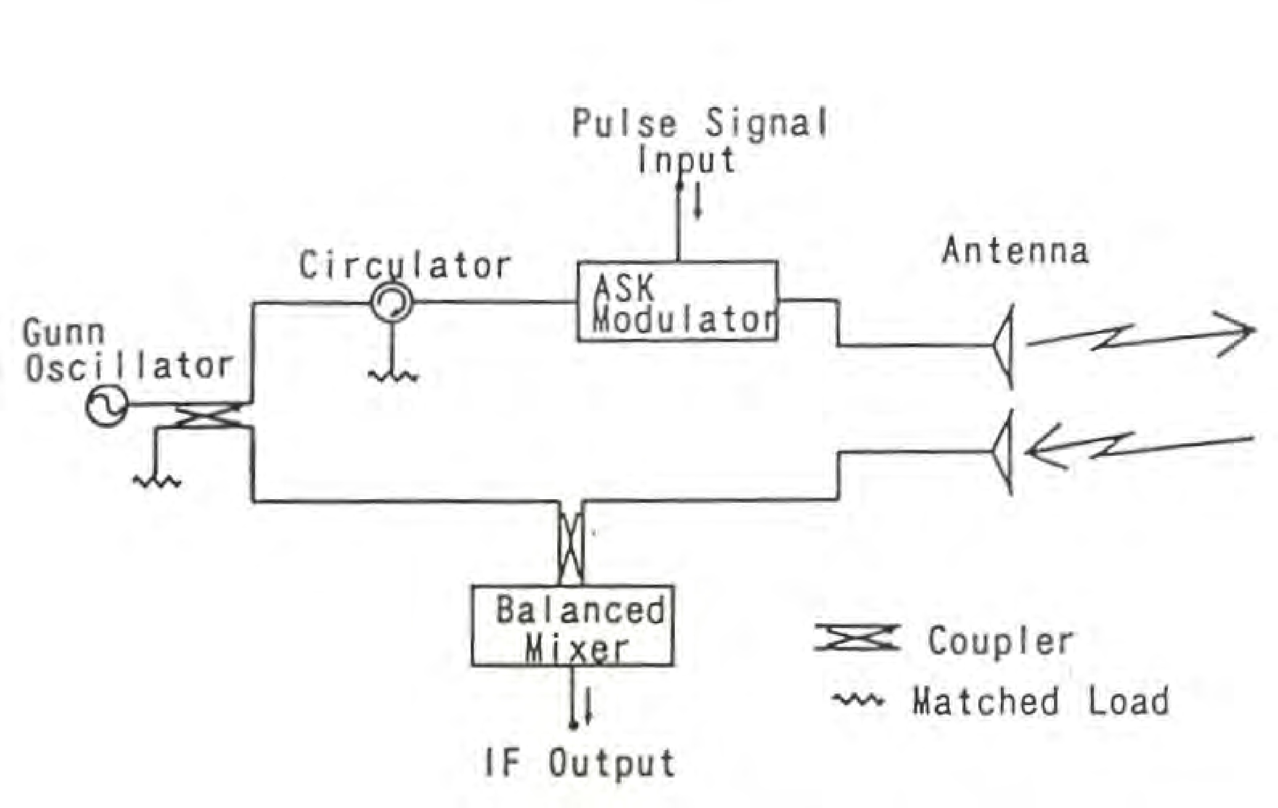




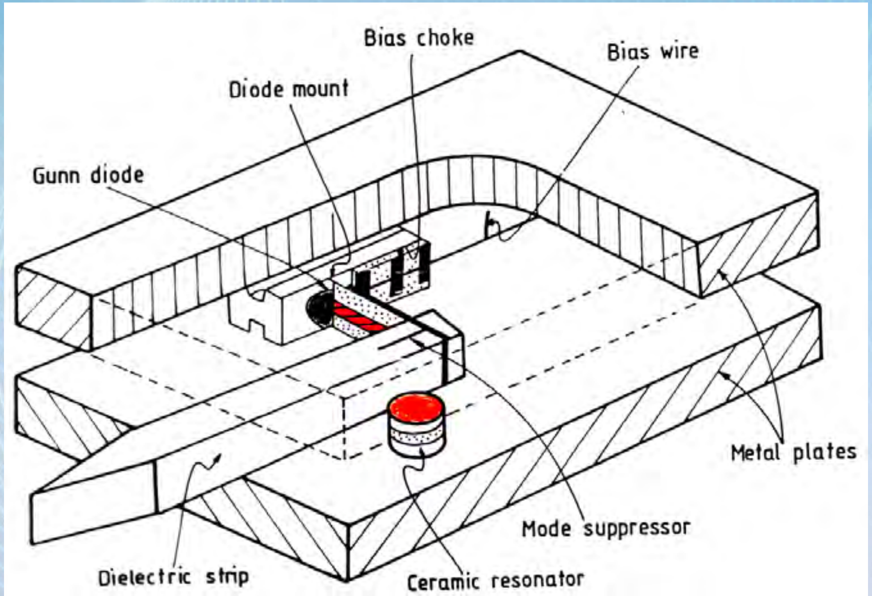
Source: Yu Zhan et al, 2023 IEEE APCAP Conference Digest

35 GHz Non-Radiative Dielectric Transceiver

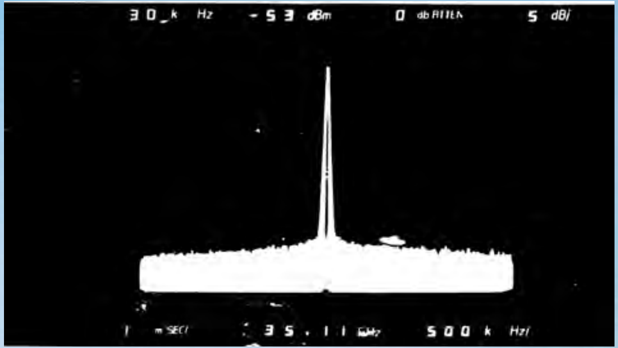
Block Diagram of Millimeter Wave Digital Transceiver



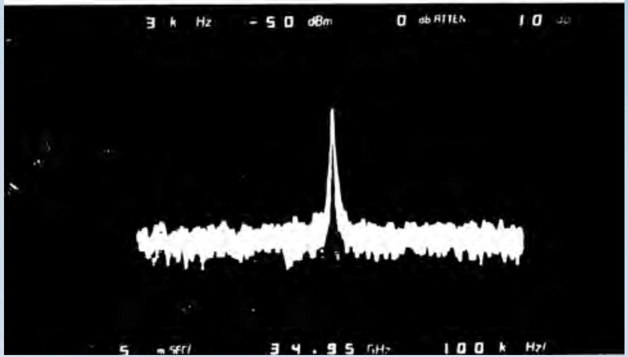
35 GHz Non-Radiative Dielectric Transceiver



Cut away view of Gunn Oscillator in NRD Guide

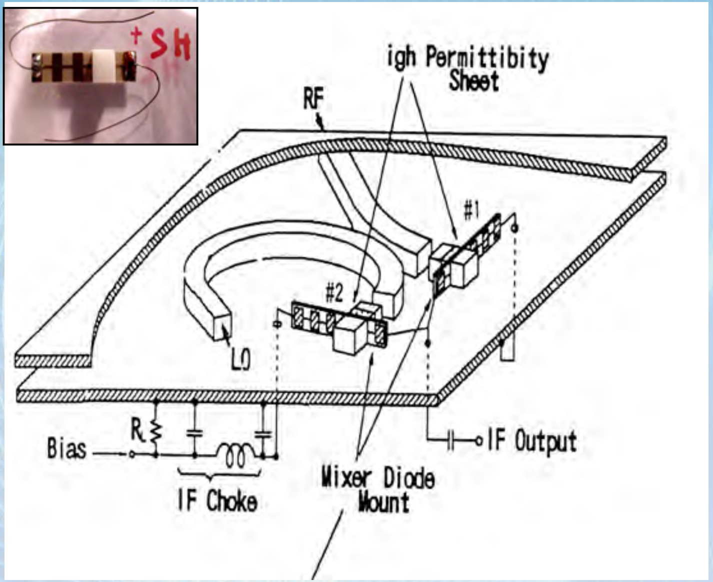


Transmitter Oscillator Spectrum

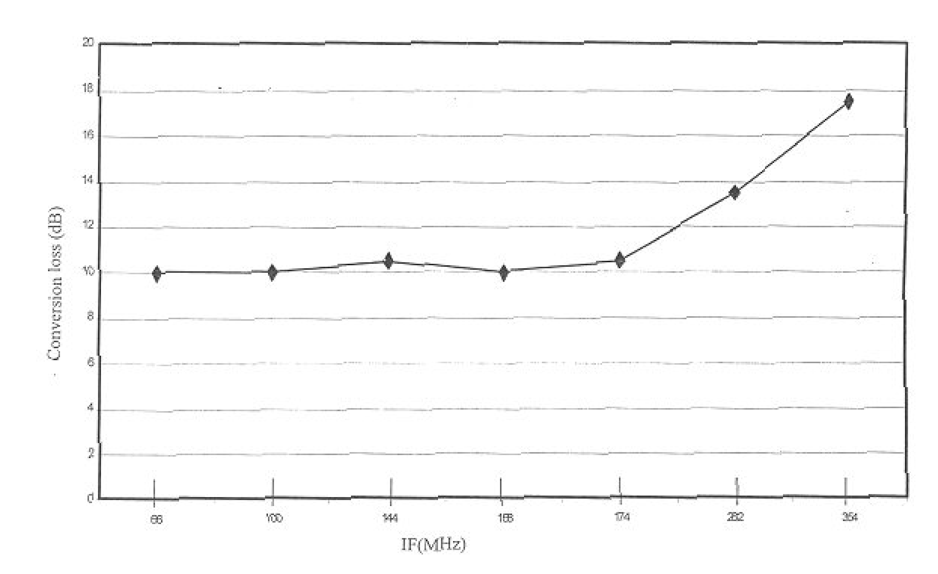


Receiver Oscillator Spectrum

35 GHz Non-Radiative Dielectric Transceiver

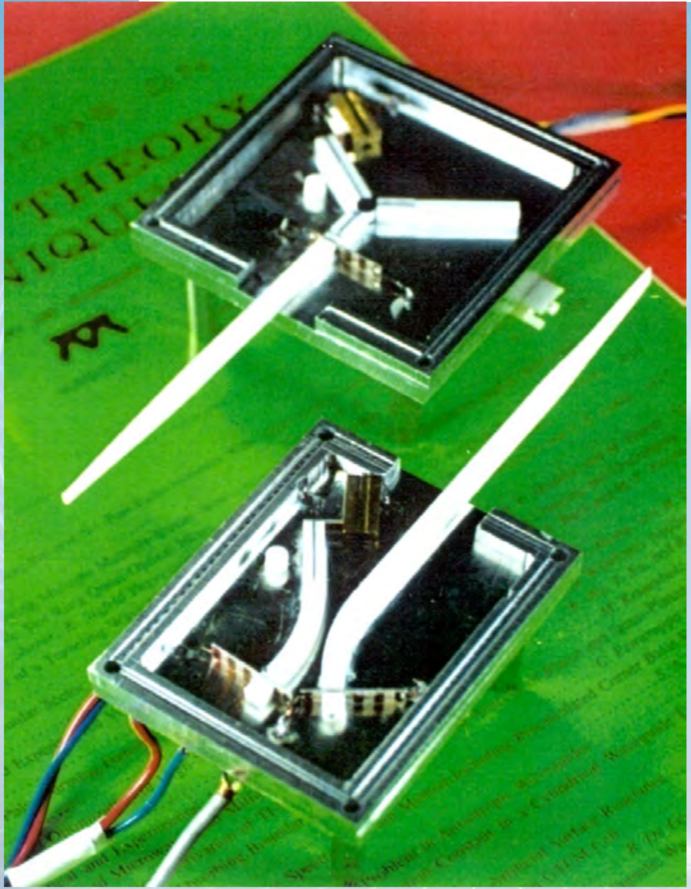


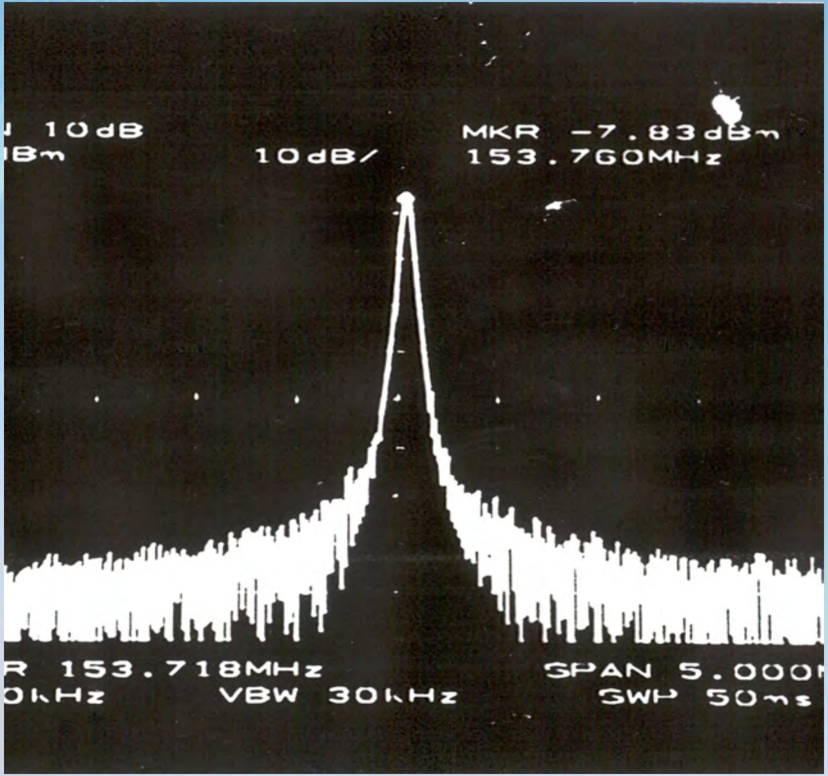
Layout of Balanced Mixer in NRD Guide



Mixer Conversion Loss

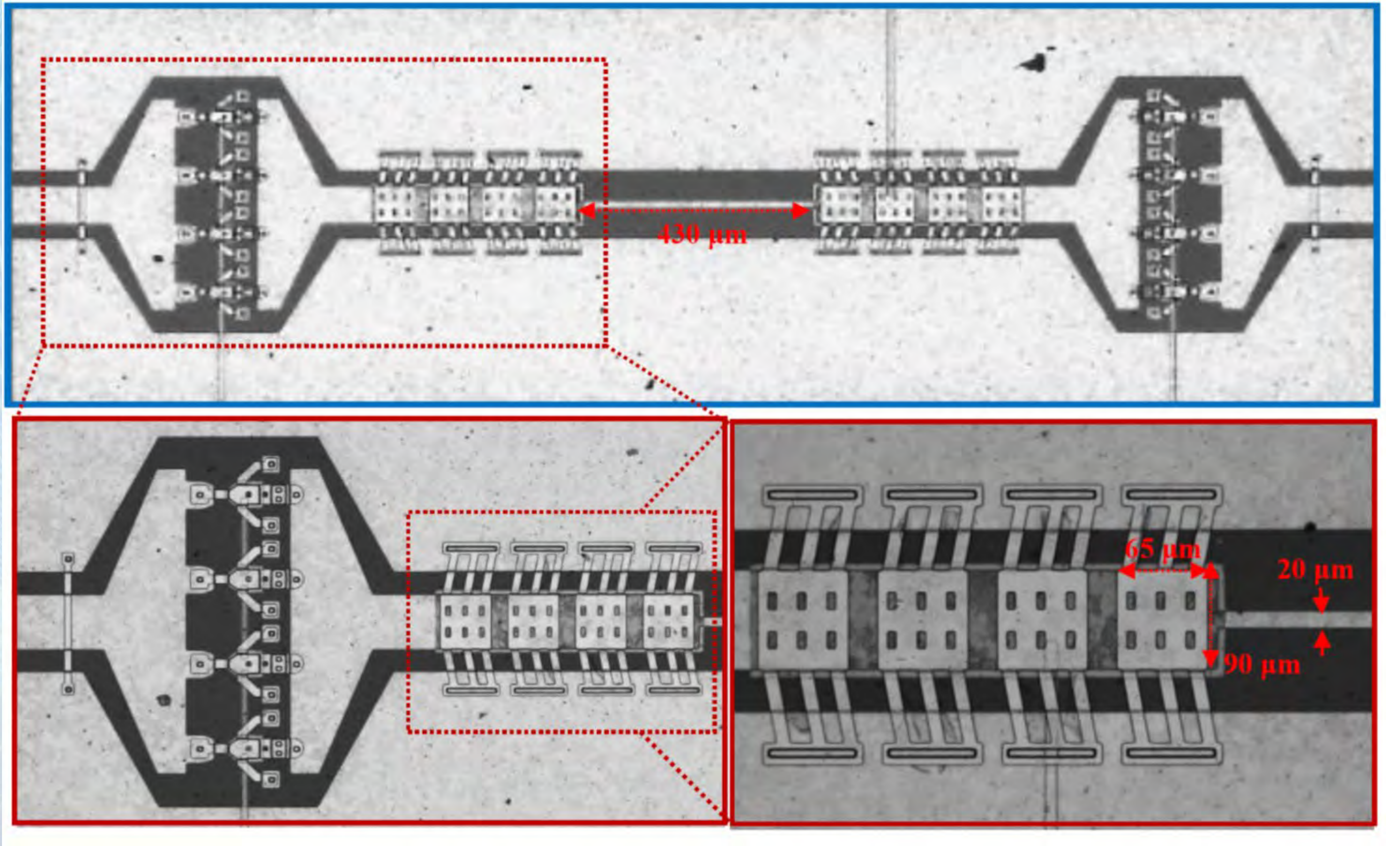
Non-Radiative Dielectric Guide Transceiver



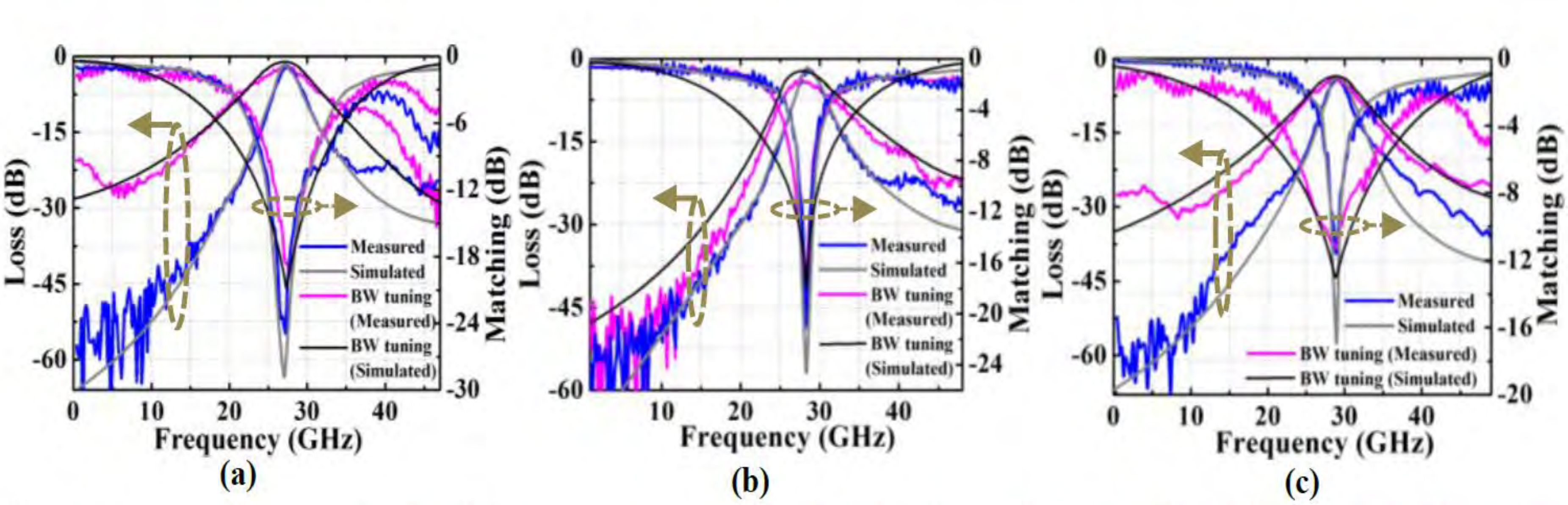


IF Spectrum

Micromachined Circuits-Tunable Filters



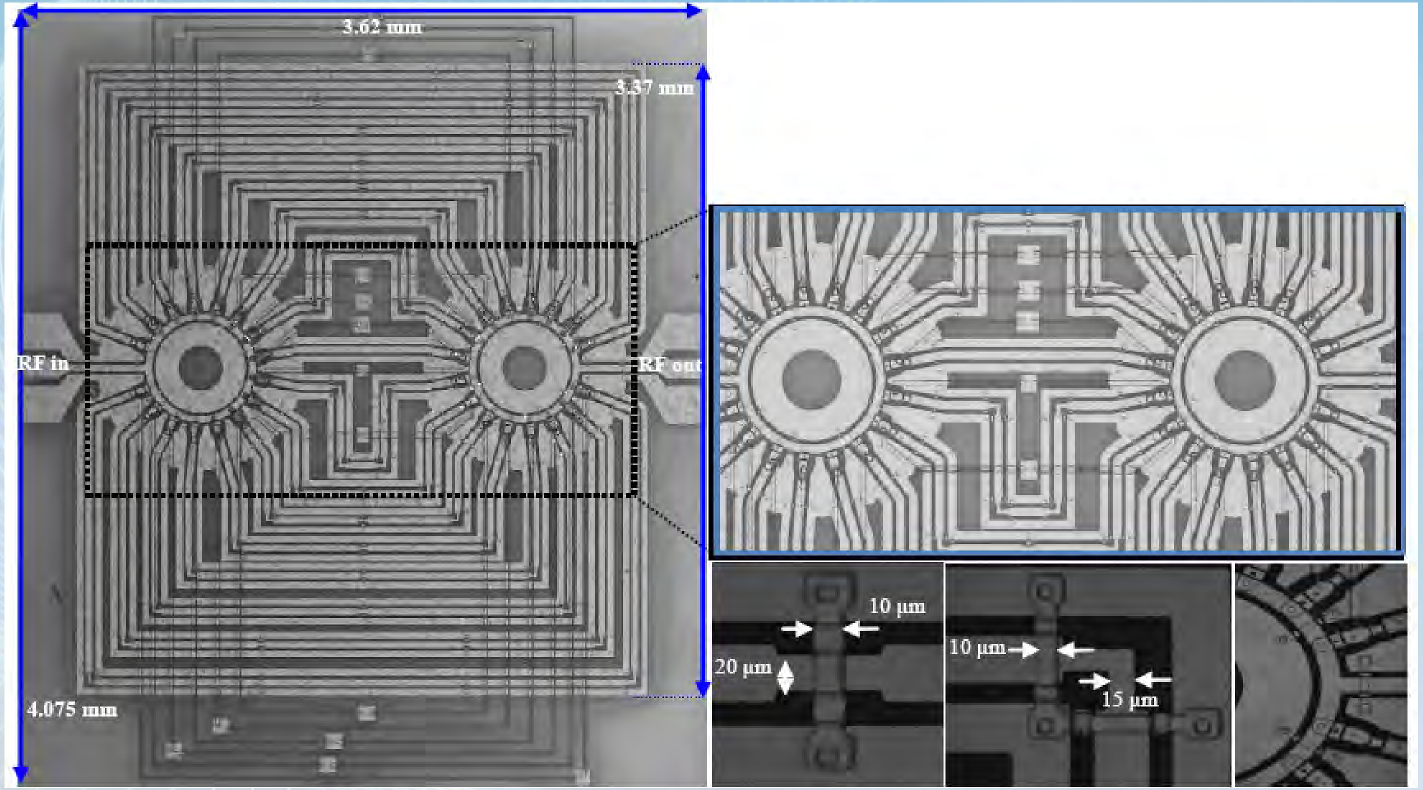
Micromachined Circuits-Tunable Filters



Note: Bandwidth as well as Centre Frequency tuning can be done

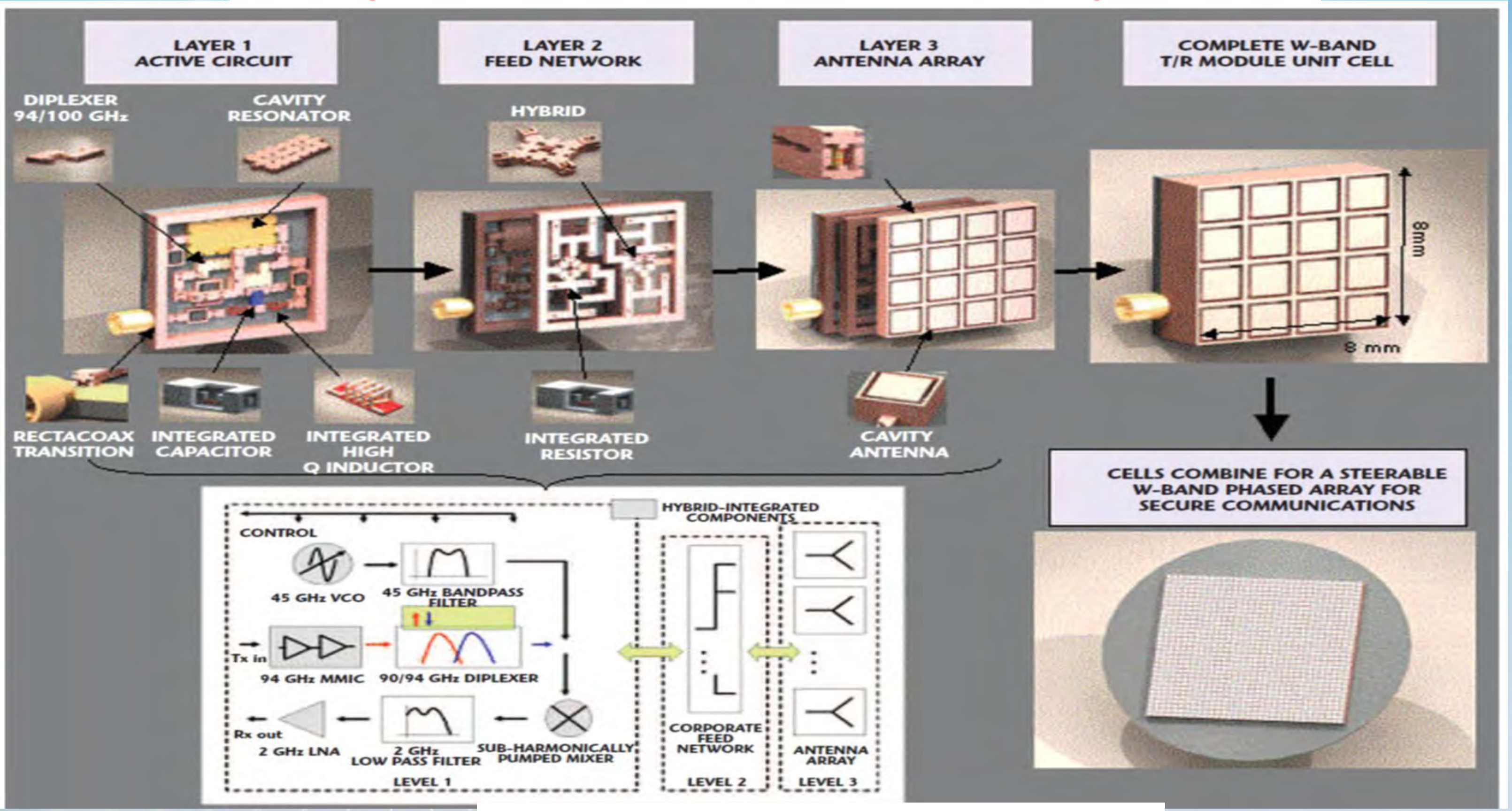
Source: S. Dey and Shiban K. Koul, "Reliable, Compact, and Tunable MEMS Bandpass Filter Using Arrays of Series and Shunt Bridges for 28-GHz 5G Applications," IEEE Transactions on Microwave Theory and Techniques, Published 10 November 2020.

Micromachined Circuits-Phase Shifter



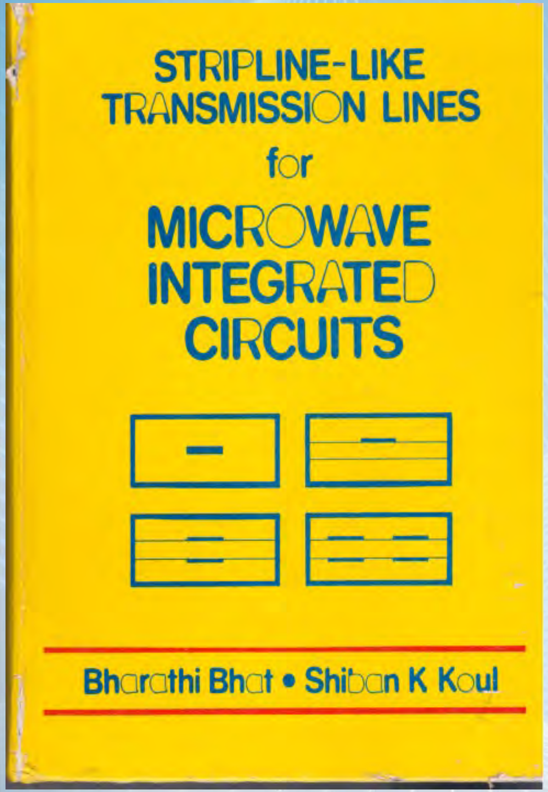
Source: Sukomal Dey and Shiban K Koul, MEMS K-band 4-bit phase shifter using two back-to-back SP16T switching networks", IEEE Journal of Micro-electro-mechanical System , August 2018

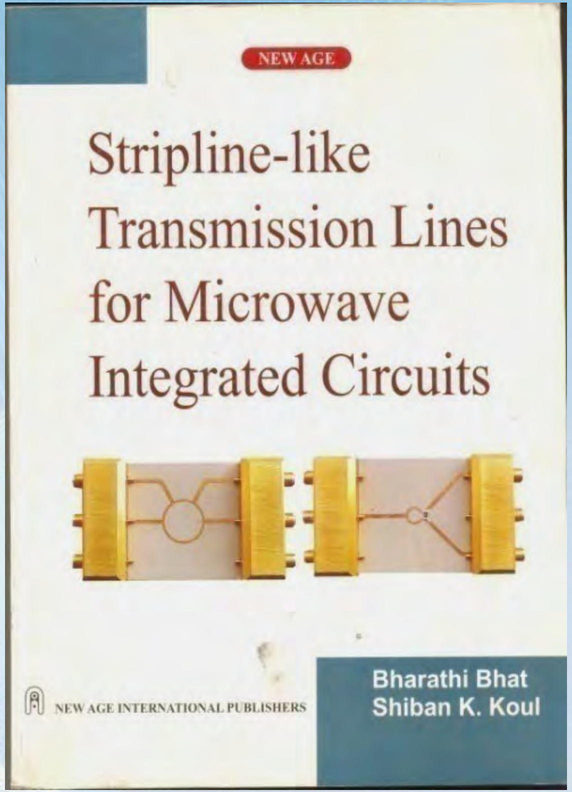
Polystrata Circuits and Subsystems

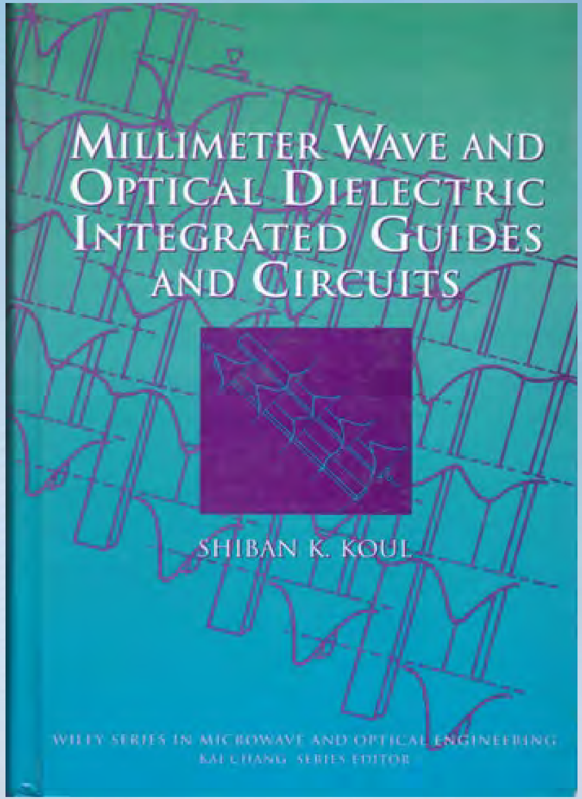


Source: Microwave Journal, February 2008 issue

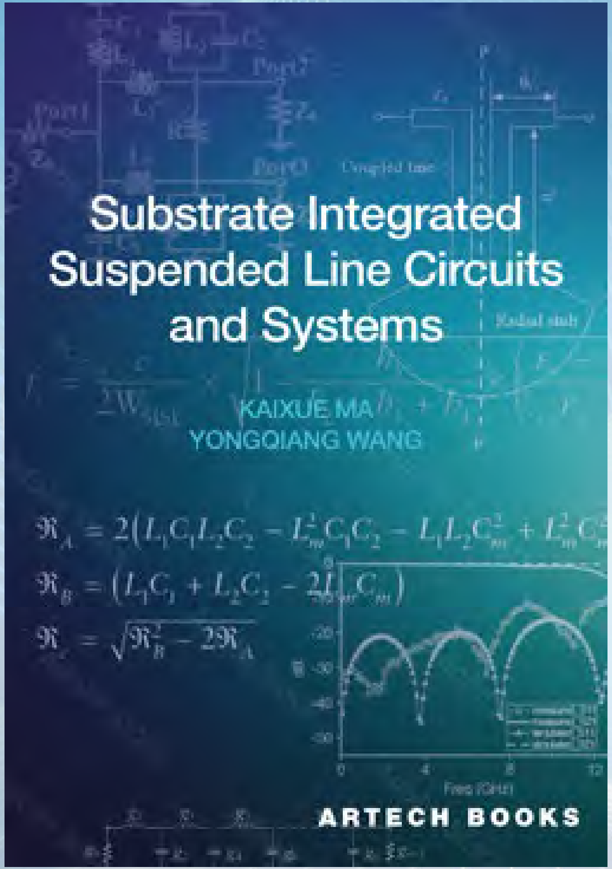
Reading Material

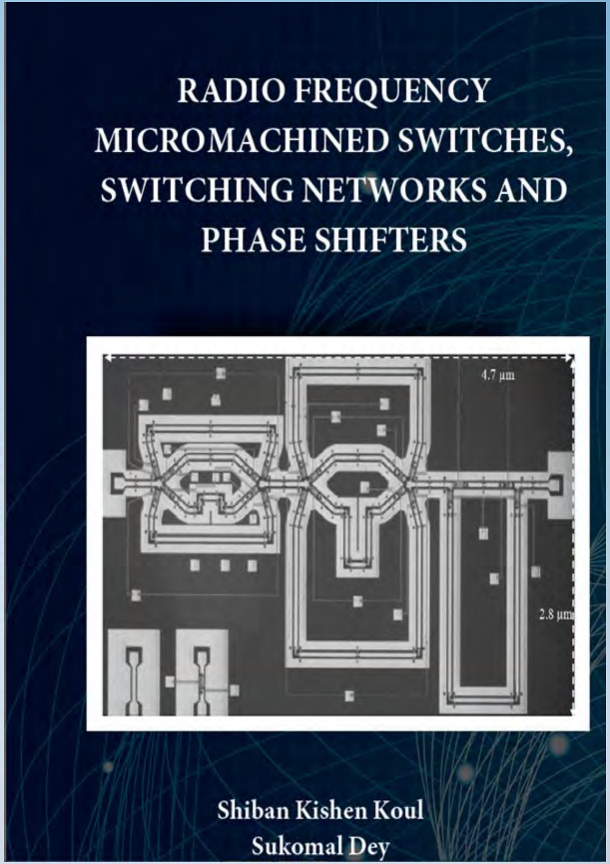




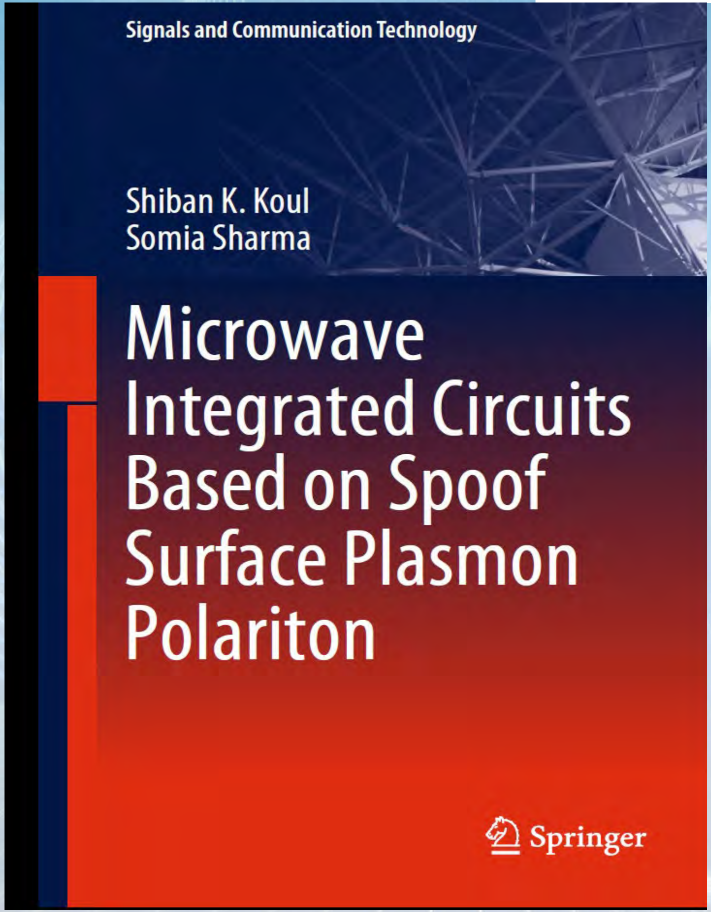


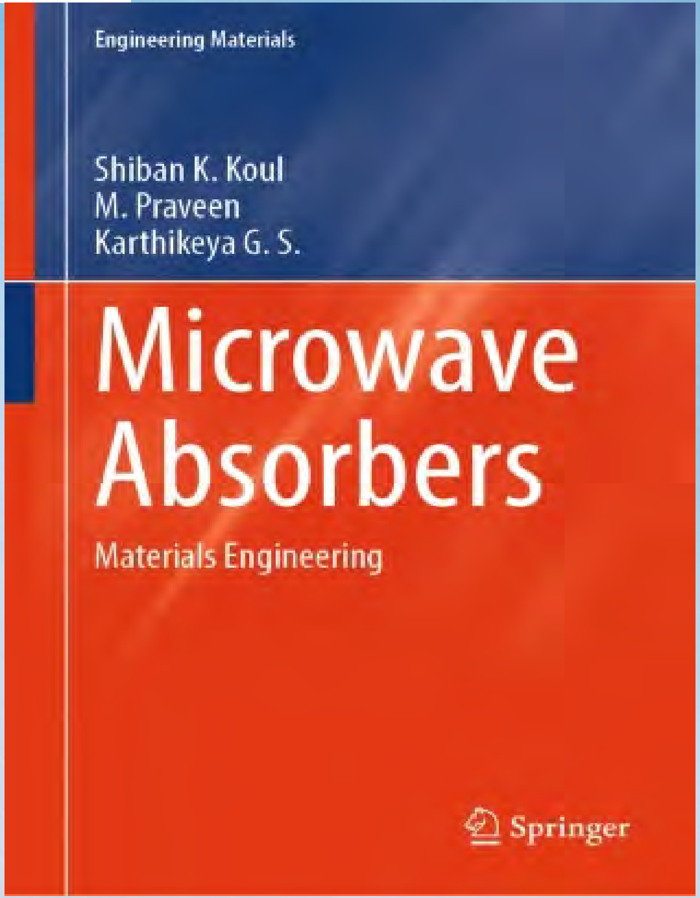
Reading Material





Reading Material





Thank You for Your Kind Attention

s.k.koul@ieee.org