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Exploration of High-Q Resonator based Topologies on Silicon and GaAs at Radio Frequencies

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Abstract: *Resonator with higher quality factor is desirable to achieve low insertion loss at microwave and millimetric frequencies. High quality factor-based resonator integrated with active circuitry results in the topology with low loss and further implementation on GaAs eliminates off chip parasitic associated with bond wires and interconnections. The main challenge lies in the incorporation of the high Q resonator in monolithic form which can be achieved by employing micromachining techniques. This article describes various methodologies, implementation plans, fabrication sequence of various topologies which are explored based on the ease of realization and inherently resulting in high quality factor-based resonator. Oscillator topologies having micromachined resonator and active patch working as resonator are the topologies taken for study and FEM based simulation carried out along with detailing of process steps. Selection of the topology and mathematically equations are also presented in the article.*

Keyword: *Resonator; sensor; oscillator; radio-frequency; micromachining*

1. INTRODUCTION

The integration of active circuitry with resonator at higher end of radio-frequency such as amplifiers, oscillators etc. have the limitations of implementation with hybrid approach. The hybrid approaches optimize each circuit performance and interconnect them to have system level implementation. The oscillator is one of the basic topologies which is challenging to implement at higher frequencies due to associated phase noise and inferior performances due to lumped quality factor associated with planar topology. At higher frequencies various multipliers after the oscillators are incorporated to have desired performances related with phase noise and spurious. Alternatively, at higher end of frequencies achieving the stable frequency directly result in compactness and higher reliability of the circuit. Broadly two topologies are employed for oscillator implementation- transmission type and reflection type at higher frequencies. The requirement for the resonator is of higher Q and planar configuration. This will result in repeatability, reduction in losses, size reduction, and weight improvement compatibility while integrating other structures. Transmission type topology compared to reflection type topology having parallel feedback results in greater efficiency, loss reduction, no mode jumping and stable output power.

In the transmission topology the resonator acts as band pass filter whereas in the reflection type it acts as band stop filter. Reflection type employs line along with external dielectric resonator. Generally external dielectric resonator (DR) has been placed to enhance stability by increasing the loaded quality factor of the circuit [1]. Configurations such as series and shunt are chosen for the above-mentioned oscillator. The main bottleneck is to fix the DR position externally which is tedious and cause repeatability issue. Also the inherent variation of the intrinsic parameters of the device changes the output characteristics resulting in device to device variation.

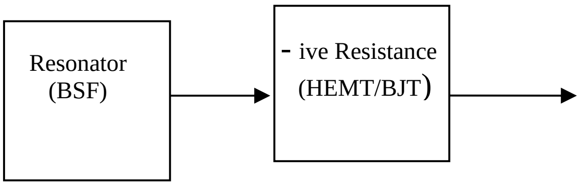

Fig 1.0: Reflection type topology

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The second configuration (transmission type) employs an amplifier with proper feedback loop containing resonator connecting output with the input. This configuration eliminates the dependence of the inherent device parameter variation resulting in more reliable and repeatable configuration. The feedback loop also employs a resonator which is band pass in nature. The requirement for the resonator having higher Q along with planar configuration yields in the repeatability and lower losses.

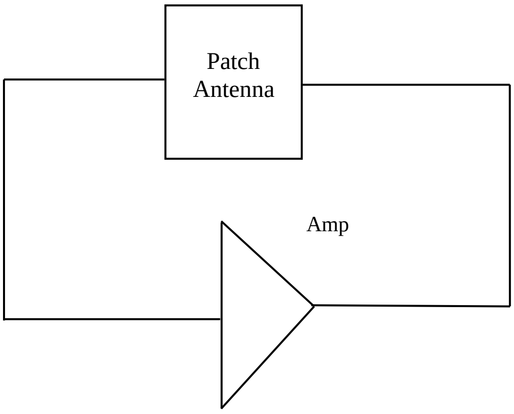


Fig2.0 Transmission type topology

Transmission type employs amplifier in closed loop configuration which eliminates dependence on parameter variation. This topology, as compared to reflection type topology, results in reliable and repeatable performances.

Active circuit realization using HEMT is preferred due to achievable performances at higher frequencies. Alternatively, concept of active antenna incorporating active part (amplifier) integrated with patch resonator also can be categorized as amplifier, frequency conversion and oscillator type topologies (Fig 2).
Various authors presented slot [2] coupling using micromachining techniques whereas higher quality factor employing micromachining is presented by Duchamp et al [3].

The structure proposed by the Gullion et al [4] is modified in the present concept by incorporating dielectric resonator puck inside to have MDRO (micromachined dielectric resonator oscillator) concept. The proposed topology having feature of slot coupling along with the excitation of higher order modes in the micro-machined cavity results in higher quality factor. An integrated assembly employing active and resonator portion can make the structure compact and reliable. Coupling between cavities is controlled by the size, position and the orientation of the slot. Proper alignment of slot and the cavity dimension is the critical part in the structure will be. The active part can be in CPW and the transition from CPW to microstrip can be incorporated for low loss [5]. Also, possibility of having an integrated oscillator on a single chip using GaAs concept is also being looked into [6, 7].

Stability and phase noise are the two important parameters affecting the oscillator performance. The higher the Q of the structure the better phase noise it provides for the overall structure. Near the carrier phase noise is proportional to $1/Q^2$. This article details planar micromachined oscillator and novel techniques for enhancement of the overall quality factor. Various processing steps are also discussed encompassing fabrication aspects on silicon and GaAs.

2. PROPOSED TOPOLOGIES

The proposed assembly will be having slot coupling and excitation of higher order modes in the micromachined cavity itself. Coupling between cavities is controlled by the size, position and the orientation of the slot as shown in Fig3.0. It consists of two wafers where coupling to second wafer is through the slot [8]. The second wafer is micromachined and attached with the first one through bonding.

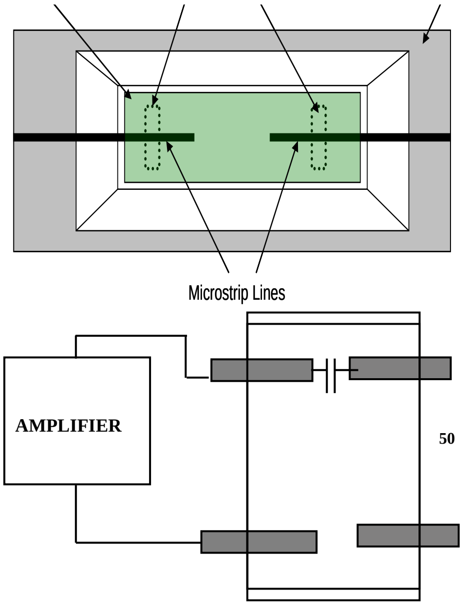


Fig 3.0: Slot coupling and micromachined oscillator concept

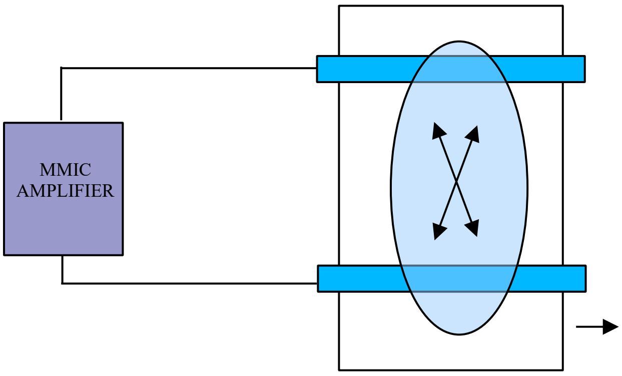
Another version of putting DR on to the open-ended line and excitation of higher order modes can also results in achieving higher Q [9]. The quality factor of the proposed topology the same can be calculated using the below formulae:

$$Q_l = \frac{f_0}{\Delta f_{3-dB}}$$

$$S_{21}(dB) = 20\log_{10}\left(\frac{Q_l}{Q_e}\right)$$

$$\frac{1}{Q_l} = \frac{1}{Q_u} + \frac{1}{Q_e}$$

Another concept presented is having patch and amplifier on the single wafer which can be implemented on the GaAs wafer (Fig5).



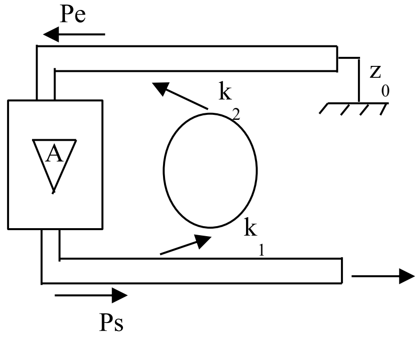


Fig 4.0: Higher order mode excitation

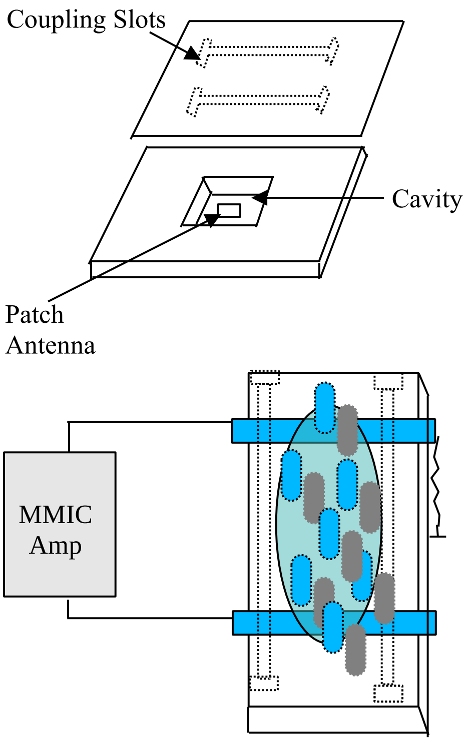


Fig5.0: GaAs based single wafer implementation

Total quality factor of the assembly can be calculated as

$$Q_r = \frac{\omega W_T}{P}$$

$$W_T = \frac{1}{4} h A \varepsilon_0 \varepsilon_r$$

$$Q_C = h\sqrt{f\pi\mu\sigma}$$

$$Q_d = \frac{1}{\tan\delta}$$

$$\frac{1}{Q_T} = \frac{1}{Q_r} + \frac{1}{Q_d} + \frac{1}{Q_{sur}} + \frac{1}{Q_r}$$

$$\frac{1}{Q_T} = \frac{P_d + P_r + P_{sur} + P_c}{\omega W_T}$$

→ Circular patch is selected instead of square one as circular patch is small compared to square one. The patch dimensions can be calculated as:

$$F_{nm} = \frac{X'}{2\pi a_e \sqrt{\varepsilon_e}}$$

Where X' is the nth root of the Bessel function of order m and radius a_e is given as

$$a_e = a\left[1 + \left(\frac{2h}{\pi a \varepsilon_e}\right)\left(\ln\frac{\pi a}{2h}\right) + 1.7726\right]^{\frac{1}{2}}$$

where $\varepsilon_e = \dfrac{\varepsilon(h+d)}{(h+t.\varepsilon)}$

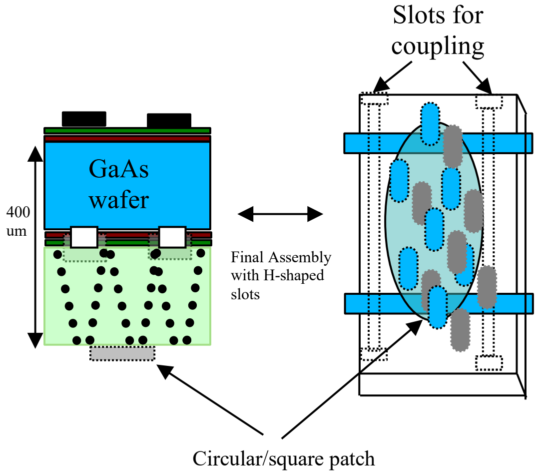


Fig 6.0: Concept of active antenna along with resonator [6]

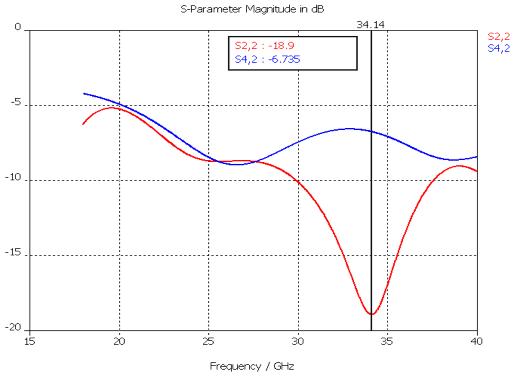
Due to fringing fields effective radius is

$$a_{eff} = a_1\left[1 + \left(\frac{2h}{\pi \varepsilon_e}\right)\left[\left(\ln\frac{a_1}{2h} + 1.41\varepsilon_e + 1.77\right) + \frac{h}{a_1}\left(0.268\varepsilon_e + 1.65\right)\right]\right]^{0.5}$$

$a_1 = \sqrt{A}/\Pi$ where A is the area

3. SIMULATION STUDY

FEM based simulation study is performed and slot coupling methodology in the silicon and GaAs taken for the analysis. Further simulation with DR puck inside the micromachined cavity in the second wafer is carried out and response at Ka-band as shown in Fig 7.0.



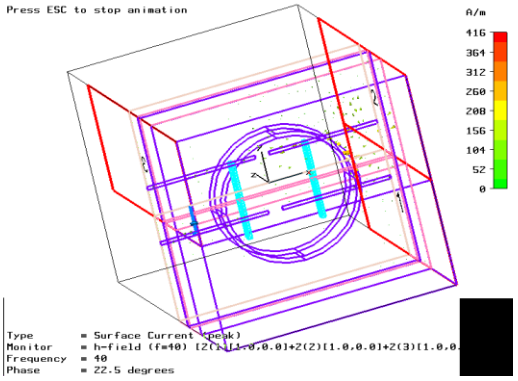


Fig 7.0: Slot coupling in the cavity

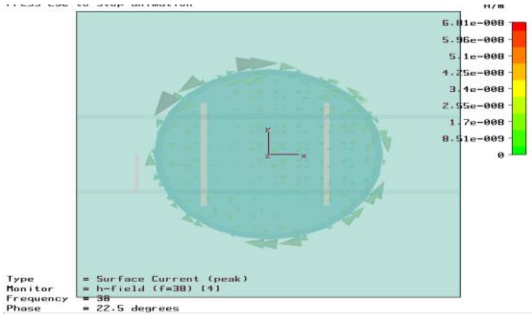
Another aspect of inserting the DR puck (R radius) inside the cavity and the same can be carried out as per below calculation:

$$R(radius) = 1.2035\left(\frac{c}{\omega}\right)\times\left[\frac{1}{\varepsilon_r}+\frac{1}{\varepsilon_s}\right]$$

$$H(height) = 0.4\times(2R)$$

$$Cover - H = 0.8\times\omega\times(2R)$$

where ε_r is the substrate dielectric constant, ε_s is the resonator dielectric constant



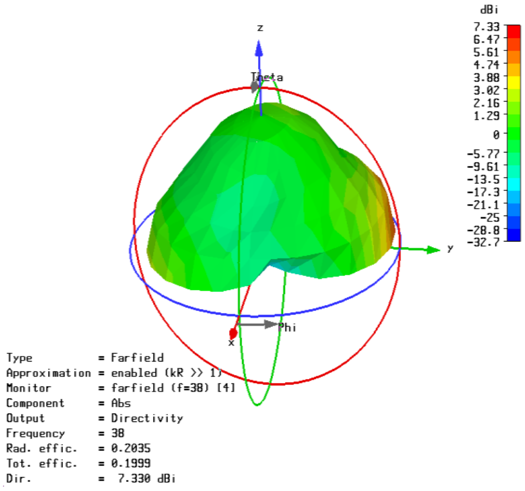


Fig 8.0: Active patch antenna simulation using FEM

The DR puck enhances the quality factor manifold and provide stable oscillator with low phase noise. [10-12] The above topologies require micromachining and via process to be established. The bulk micromachining process detailed in below section followed by detailing of overall fabrication process.

4. BULK MICROMACHINING

Bulk micromachining process uses various etchants such as ethylenediamine pyroatechol (EDP), potassium hydroxide (KOH) and tetramethyl ammonium hydroxide (TMAH) The etching in silicon is dependent on the crystallographic orientation resulting from isotropic or anisotropic etching. Silicon etches out isotropically in all directions independently using wet methodology and is dependent on time, temperature and etchant concentration. HNA solution yield isotropic etching in silicon whereas anisotropic wet etchants for micromachining are KOH, EDP, TMAH, Hydrazine where TMAH ((CH3)4NOH) is generally employed due to CMOS compatibility as alkali metal ions are detrimental to CMOS structures. Conventional alkali metal hydroxide (KOH) etching provides well-defined pattern but possibility of pyramidal hillock on the etched surface exists and possibility of hole formation on etched membrane in case of hydrazine is reported. Ethylenediamine-pyrocatechol (EDP) and Hydrazine solutions are carcinogenic and toxic. EDP and TMAH chemicals are having minimal effect on oxide layer along with smooth surface. The various steps taken for bulk micromachining are:

1. Screen Oxidation [CVD process]
2. Substrate mask and etching [Lithography]
3. Implantation (if required)
4. Metal deposition [Sputtering]
5. Metal etching [Wet/Dry etching]

6. Backside Oxide stripping [Etching]
7. Backside thick oxide deposition [CVD]
8. Back side silicon etch

Various masks such as slot, metal and cavity are employed to realize the structures. The wet etching is crystallographic dependent and primarily <100> oriented silicon wafer is taken for the processes. Both the processes are initiated with cleaning using RCA-1and RCA-2. Wet processes are faster but due to anisotropic etching the controlling of the exact depth is difficult is difficult and can be easily overcome by employing SOI wafer [13]. The etched roughness strongly depends on the crystallographic orientation.

5. FABRICATION PROCESS

The critical part in micromachining structure is the fabrication process to achieve well-defined surfaces to achieve desired performances at the desired band. GaAs and Silicon processing involves different steps and the structure needs at least 2-wafer for the complete processing. The techniques presently available on silicon wafer are:

5.1 Front Side Processing

Deposition of Si_3N_4/SiO_2 layer with Si_3N_4 followed bySiO_2. Chemical vapour deposition LPCVD for both side deposition simultaneously followed by metal deposition using sputtering or evaporation technique.

5.2 Back side processing

Slot opening by using double sided aligner (optical aligner) followed by etching

Second Wafer: Microamchining step carried out by dry/wet etching using DRIE/KOH according to the requirement of the side walls as 90° or 54.7°.
Corners will be sharp and surface roughness in the range of 10-28nm. . Taking MMIC chip and bonding with the resonator.

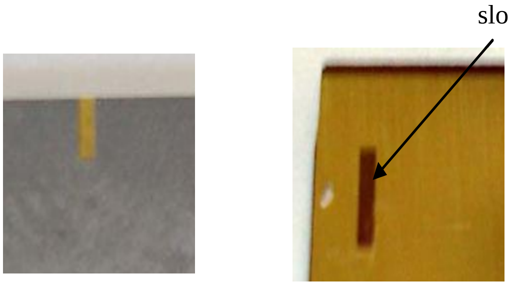


Fig 9.0: Line and slot on the high resistivity silicon wafer

The processing in GaAs is complicated compared to silicon due to uncontrolled etching phenomena associated with the wet etching.

Steps required for processing of resonator in GaAs front-end processing (dielectric and metal deposition) back side processing (bulk micromaching of the cavity). The front side processing steps are:

- Deposition of SiN layer using PECVD or polyimide film by spin coating of thickness1-2 um
- Metal deposition using litho and etching process/lift off process
- Back side patterning to remove GaAs using RIE (Reactive ion etching)/wet etchants

Another aspect of achieving the same topology on GaAs necessitate development of etching and via process. The various trials carried out for achieving via in the GaAs carried out and SEM of the via is shown in Fig 10.0.

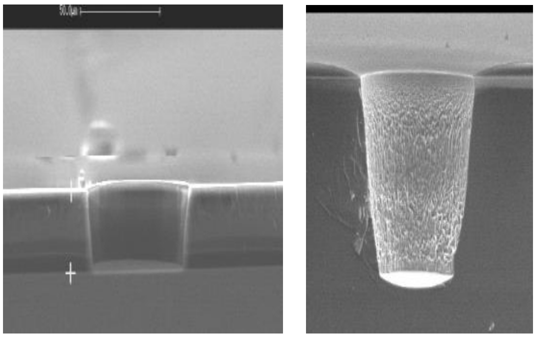


Fig10.0: Via in GaAs and the cross-section view

6. CONCLUSION

Proposed structures having the resonator configuration with slot coupling excite higher order modes. The micromachined cavity can be incorporated in this structure to have higher Q. The critical part of the structure realization necessitate proper alignment of slot and the cavity dimension. Coupling between cavities is controlled by the size, position and the orientation of the slot. Concept of realization high-Q structure both on the silicon and GaAs wafer are presented.

An integrated oscillator having active and resonator part on the same chip can be realized on the GaAs wafer and incorporation of the DR inside the cavity (silicon wafer) or via concept in GaAs are the alternatives to achieve higher Q assembly. The first topology can be implemented on the silicon wafer and second topology on the GaAs wafer integrating the two-wafer concept. This can be converted to a complete active antenna as discussed in the article.

The structure results in the higher quality factor along with the additional features inherent in the proposed topology are: much higher quality factor, elimination of various parasitic, excitations of higher order modes.

7. ACKNOWLEDGEMENTS

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REFERENCES

[1] Kamaljeet Singh, and S.Pal **,"**CAD implementation of DR based oscillator using Non- linear Analysis," RF Design, ,pp32-36, March 2007

[2] John Papapolymerou,Cheng,East and Katehi," A micromachined high Q X Band Resonator", IEEE Microwave and Guided Wave Letters,Vol 7,Issue 6,pp 169-170,June 1997

[3] G.Duchamp,L.Casadebaig et al " A novel tool for slot-microstrip transition simulation", IEEE Microwave and Guided wave Letters,Vol 7,Issue 9,Sept 1997

[4] B.Gullion et al ", Design and Realization of high Q millimeter wave structures through micromaching techniques", IEEE MTT-S International Symposium ,1999

[5] Hill, Papapolymerou and Ziolkowiski"High Q micromachined resonant cavities in a X band diplexer configuration", IEE Proc. Microwave and Antenna Propogation,Vol 148,Issue 5,pp 307-312,Oct2001.

[6] Heide,Schubart,"24 GHz low loss Doppler Sensor with fundamental frequency GaAs pseduomorphic HEMT oscillator stabilized by DR operating at Higher order modes," IEEE MTT-S Int. Microwave Symposium,May1994

[7] Salzentein,Dupusis et al," Coplanar waveguide on dielectric membrane micromachined on GaAs substrates," Electronics Letters,Vol 32, Issue 9, April 1996,pp 821-822

[8] K.Singh & K Nagachenchaiah,: Effect of resistivity variations on the performance of lossy micromachined resonators," Microwave Journal, 2008, pp 112-118

[9] Kamaljeet Singh & Surendra Pal,"Micromachining concept on GaAs and its application in active and passive circuits at milllmetric wave frequencies," High frequency Electronics ,Oct 2007

[10] Yateendra Mehta, Kamaljeet Singh, R.Ramsubramanian," Design and development of stable DRO at S-Band ", International Radar Symposium, Bangalore, 2005

[11] Inder Bahl," Microwave Solid State Circuit Design," Wiley Interscience, Second Edition, 2003

[12] Fiedzuszko & Holme' Dielectric Resonatore-Raise your high-Q',IEEE Microwave magazine 2001,pp 51-60

[13] Prem Pal & Kazuosato,Silicon Wet Bulk Micromachining for MEMS, Pan Stanford Publishing Pte Ltd,2017

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