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# High performance tunable slow wave elements enabled with nano-patterned permalloy thin film for compact radio frequency applications

B. M. Farid Rahman,[1] Ralu Divan,[2] Hanqiao Zhang,[3] Daniel Rosenmann,[2] Yujia Peng,[1] Xuehe Wang,[1] and Guoan Wang[1,a)]

[1]*Microwave Applications Group, Dept. of Electrical Engineering, University of South Carolina, Columbia, South Carolina 29208 USA*
[2]*Center for Nanoscale Materials, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[3]*Intel Corporations, Columbia, South Carolina 29210, USA*

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Slow wave elements are promising structures to design compact RF (radio frequency) and mmwave components. This paper reports a comparative study on different types of coplanar wave-guide (CPW) slow wave structures (SWS). New techniques including the use of defected ground structure and the different signal conductor shape have been implemented to achieve higher slow wave effect with comparative loss. Results show that over 42% and 35% reduction in length is reported in the expense of only 0.3 dB and 0.1 dB insertion loss, respectively, which can end up with 66% and 58% area reduction for the design of a branch line coupler. Implementation of the sub micrometer patterned Permalloy (Py) thin film on top of the simple SWS has been demonstrated for the first time to increase the slow wave effect. Comparing with the traditional slow wave structure, with 100 nm thick Py patterns, the inductance per unit length of the SWS has been increased from 879 nH/m to 963 nH/m. The slow wave effect of the designed structure is also tunable by applied DC current. Measured results have shown that the phase shift can be changed from 94° to 90.5° by applying 150 mA DC current. This provides a solution in designing RF passive components which can work in multiple frequency bands.  [http://dx.doi.org/10.1063/1.4862847]

## I. INTRODUCTION

Passive components take 80% of the board area which contribute to 70% of the total cost in a RF (radio frequency) communication system. Slow wave structures[1–3] have been widely studied to design compact RF passive. As per transmission line theory, the wavelength, phase velocity, and characteristics impedance are given as

$$\lambda = \frac{v}{f}, \tag{1}$$

$$v = \frac{1}{\sqrt{LC}}, \tag{2}$$

$$Z_0 = \sqrt{\frac{L}{C}}. \tag{3}$$

Increase of inductance (L) and capacitance (C) with the same ratio can reduce the wavelength and speed of signal transmission while keeping the characteristics impedance same.

SWS can be realized by placing an alternating narrow and wide conductor sections. But this will contribute higher insertion loss due to increased mismatch. To improve the loss by introducing the cross-tie periodic structure[4] and in homogenously doped semiconductor structure[5] have been reported. But fabrication can be a big issue for this. In this paper, CPW slow wave structures having different shapes are analyzed and optimized to achieve high slow wave effects with low loss. Sub micrometer patterned Py is integrated in the slow wave structure to further increase the inductance value. Permeability of patterned Py is tunable with DC current,[6] tunable slow wave structure is demonstrated for the first time in this paper.

## II. EXPERIMENT

CPW slow wave structures with various shapes and optimized designs are fabricated with 0.9 $\mu$m thick gold on high resistivity (10 k$\Omega$-cm) silicon substrate as shown in Fig. 1. For tunable SWS, 100 nm thick Py is deposited on top of

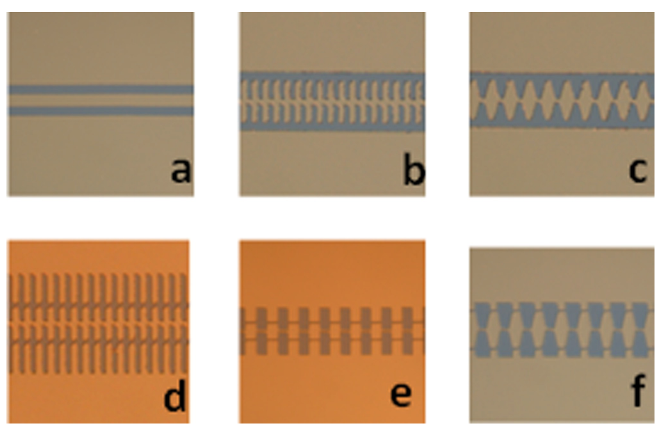


FIG. 1. (a) Regular non-SWS, (b) Step type SWS, (c) Zigzag type SWS, (d) Defected ground type SWS, (e) Optimized defected ground with step type signal structure, and (f) Optimized defected ground with zigzag type signal structure.

[a)]Author to whom correspondence should be addressed. Electronic mail: gwang@cec.sc.edu.

 

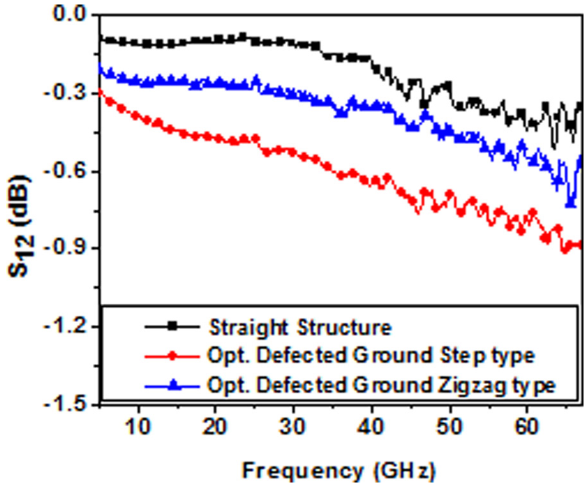


FIG. 2. $S_{12}$ (dB) of optimized SWSs and regular non-SWS.

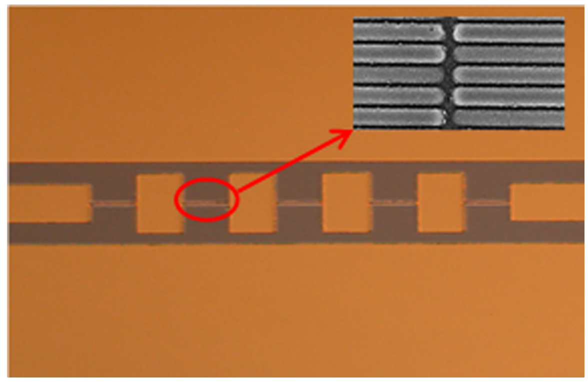

FIG. 3. Permalloy embedded SWS. Sub micro meter patterned Py is shown at inset.

narrow portioned signal line responsible for larger L [Fig. 3]. Chromium (Cr) (5–10 nm) was used as an adhesion layer between Au and Py. E-beam lithography is used to pattern Py at sub-micrometer range.

The S parameters are measured with a ZVA67 network analyzer. Equations[7] are used to extract RLGC parameters. DC current is applied using bias tee in order to tune inductance value. Standard TRL calibration is used to de-embed the loss from cables, connectors and RF probes.

## III. RESULTS AND DISCUSSION

SWS with step type signal structure is designed as shown in Fig. 1(b). Higher distance between narrow conductor and ground will increase L, while lower distance between wide conductor and ground will increase C. This will ensure better size reduction but increased mismatch will result in more loss. That is why new defected ground type structures are introduced in Fig. 1(d). At step type structure [Fig. 1(b)], increase of the inductance and capacitance value by 27% resulted in a quarter wave length of 382 $\mu$m compared to 487 $\mu$m for normal structure, i.e., 21% reduction in length. This size reduction is achieved with the sacrifice of 0.15 dB insertion loss. At Zigzag structure [Fig. 1(c)], inclined transition from narrow conductor to wide conductor minimized insertion loss by 0.06 dB compared to step type structure.

Defected ground type structure along with step [Fig. 1(e)] and zigzag type [Fig. 1(f)] signal conductor is further optimized to achieve higher slow wave factor with reasonable insertion loss. Transmission magnitude up to 67 GHz is presented in Fig. 2. Extracted equivalent quarter wavelength and insertion loss responsible for that are compared at Table I.

Decreasing the pitch of the signal structure improved insertion loss tremendously. But it ended up with lower slow wave effect. Gap in between narrow conductor section and ground is then increased which resulted in much higher inductance value. Extension of the length of wide conductor increased the capacitance proportionately. This new technique to use different length for different sections provided us much flexibility with wave impedance value fixation. Structure in Fig. 1(e) decreased length by 41.3% and increased the insertion loss by 0.3 dB. Further reduction of insertion loss by introducing zigzag type signal conductor is shown in Fig. 1(f). It reduced size by 35.2% in expense of only 0.11 dB loss at 60 GHz.

To further increase the inductance value and to achieve a tunable slow wave structure, we demonstrated Py embedded simple slow wave structure in Fig. 3. Use of Py is restricted to lower frequency by Ferro Magnetic Resonance (FMR) because the permeability of ferromagnetic films drops below zero beyond this frequency.[8] That is why Py was patterned into small bars on top of the narrow conductor section which is mainly contributing to L value [Fig. 3]. Dimension of the Py bars was 10 $\mu$m $\times$ 150 nm. Gap in between the Py bars is 100 nm.

Frequency of ferromagnetic resonance can be described by Kittel's formula[9]

$$f_r = \frac{\gamma}{2\pi}\sqrt{(H_{Bias} + H_{Ani} + (Ny - Nz)4\pi Ms)(H_{Bias} + H_{Ani} + (Nx - Nz)4\pi Ms)}.$$

Demagnetization coefficients are approximated as Ny = .0013 (Ref. 9) and Nz = .0069, Nx = .9918 (Ref. 10) for our structure. For Permalloy, saturation magnetization, $4\pi Ms = 9$ KG and gyromagnetic ratio, $\gamma = 176$ GHz/T.[11] By fitting our results into Kittel's equation, we have estimated an anisotropy field of 45.75 KA/m which results in a FMR at 6.3 GHz.

Several researches are now under investigation in order to increase the FMR frequency to a higher value. Use of patterned thin film[12–14] and multilayer thin film[8] demonstrated an increase of $f_{FMR}$. Annealing of the film in presence of an external magnetic field showed promise.[15] Ni-Fe nanowires with small cross section areas have reported higher natural

TABLE I. Comparison of different type of SWSs.

| Structures | $Z_0$ (Ohm) | Center Freq. (GHz) | $\lambda/4$ ($\mu$m) | $S_{12}$ (dB) for $\lambda/4$ |
|---|---|---|---|---|
| Straight | 50.1 | 60 | 488 | 0.447 |
| Step | 50.8 | 60 | 382 | 0.592 |
| Zigzag | 50.1 | 60 | 403 | 0.508 |
| Def. Gnd. type | 49.8 | 60 | 340 | 0.677 |
| Opt. Def. Gnd. Step type | 50.4 | 60 | 286 | 0.751 |
| Opt. Def. Gnd. Zigzag type | 50.3 | 60 | 316 | 0.554 |

TABLE II. Comparison of Inductance value for the introduction of Py and external DC current.

| Structures | Inductance per unit length at 4 GHz (nH/m) |
|---|---|
| No permalloy | 879 |
| Py at 0 mA DC current | 963 |
| Py at 50 mA DC current | 933 |
| Py at 100 mA DC current | 914 |
| Py at 150 mA DC current | 895 |

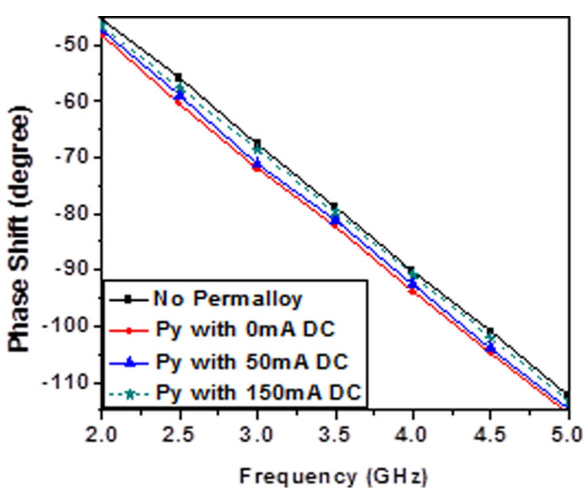


FIG. 4. Equivalent Phase change of 4.186 mm long Py embedded SWS at different DC current.

FMR frequency.[16,17] Saturation magnetization (Ms) value depends on the ferromagnetic material itself. Frequency of FMR is dependent on saturation magnetization as per Kittel's formula.[9] So the researchers are now using different materials like CoNbZr, CoZrO, CoPdAlO, CoFeAlO, Fe (Refs. 15, 18, and 19), etc.

Introduction of Py increased the insertion loss of the SWS by around .04 dB. Only 100 nm thick patterned Py increased the L value from 879 nH/m to 963 nH/m while keeping the C value almost fixed at .253 nF/m. This higher L value changed the phase shift from 90° to 94° in case of 4.186 mm long SWS. Phase shift and L value can be further improved by increasing the thickness of Py or using multi-layer Py. Application of 150 mA of DC current decreased the L value from 963 nH/m to 895 nH/m [Table II and phase shift from 94° to 90.5° [Fig. 4]. This testifies its promise for tunable SWS at multiband frequencies.

## IV. CONCLUSION

In this paper, a novel low loss slow wave structures are designed, fabricated, and demonstrated with nano-patterned Py thin film. Methods of using the defected ground structure along with the different section lengths are used for the first time in order to achieve compact SWS with reasonable loss. The defected ground structure with step type signal conductor reduced the size by 42% in exchange of 0.3 dB loss at 60 GHz. The defected ground structure with zigzag type signal conductor decreased the size by 35% in expense of 0.1 dB loss. Implementation of sub micrometer patterned Py on a simple slow wave structure showed further size reduction as well as potential for tunable SWS.


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