Numerical and Comparative Study of the Agility of Planar Transmission Lines printed on a Ferroelectric Thin Film

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A-G. Moussavou[(1,2)], V. Bouquet[(2)], R. Sauleau[(1)], A. Perrin[(2)], M. Guilloux-Viry[(2)], K. Mahdjoubi[(1)]

Abstract

In this paper, we report on simulation results at 10 GHz of planar transmission lines (TL) printed on a ferroelectric thin film deposited on sapphire and lanthanum aluminate substrates. The ferroelectric film permittivity is supposed to vary from 700 to 500. First, the main properties of microstrip (MS), coplanar waveguide (CPW) and coplanar strips (CS) namely their effective permittivity, characteristic impedance and insertion loss are computed as a function of the physical and electrical parameters. Then their tunability and figure of merit are defined and compared. CPW and CS lines present a tunability ($\Delta\varepsilon_{eff}/\varepsilon_{eff\_max}$) of about 16 % for a gap value g = 30 µm. The MS lines show a much less tenability of 2%. Moreover, the figure of merit of CPW and CS configurations are of 6.3 and 12.2 %/dB for a gap value of 30 µm, respectively. By increasing the gap, these figures of merit can be improved up to the limiting values of 8.7 and 15.4 %/dB, respectively.

Index terms: Ferroelectric thin films, Planar transmission lines, Tunability, $KTa_xNb_{1-x}O_3$, $Ba_xSr_{1-x}TiO_3$

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I. Introduction

The rapid development of microwave applications in general public telecommunications has led to a growing interest in tunable devices operating in the GHz band. Several solutions have been investigated to obtain tunability: (i) integration or mounting of lumped elements (FET transistors, p.i.n and varactor diodes…) or Micro-Electro-Mechanical Systems (MEMS), or (ii) use of agile materials. Among agile materials, ferroelectrics are of particular interest. These materials provide the possibility of tuning due to the electric field dependence of their dielectric permittivity. Moreover, ferroelectric thin films can easily be integrated within planar circuits.

Several ferroelectric devices such as phase shifters [1-3], phased array antenna [4], resonators and filters [5], varactors [6, 7], electromagnetic bandgap structures and metamaterials [8, 9] were designed and realized. Nevertheless none of these contributions investigates and compares the basic properties of printed transmission lines (effective permittivity, characteristic impedance, insertion loss, figure of merit) as a function of the permittivity of the ferroelectric thin films, although these data are of uppermost importance for the design of tunable planar circuits.

Therefore the aim of our work is twofold: (i) analysis of the potential tunability of standard transmission lines, and (ii) determination of the best configuration in terms of loss and tunability. Such data are very useful from an engineering point of view. Here the tunable range of the ferroelectric film permittivity (at room temperature) was chosen to vary between 700 at zero DC-bias field and 500 at moderated field [10, 11]. These values correspond to ferroelectric materials belonging to $KTa_xNb_{1-x}O_3$ (KTN) or $Ba_xSr_{1-x}TiO_3$ (BST) families. Whereas there is a plethora of studies using BST materials, only few papers report on KTN materials, although prior works [12, 13] have highlighted the promising performance of the latter (significant agility and reduced loss) .

Three categories of multilayer transmission lines (TL) are compared and discussed at 10 GHz (**Fig.1**): microstrip lines (MS), coplanar waveguides (CPW), coplanar strips (CS). These lines are printed on a dielectric substrate (ε_r, tanδ) of thickness h. The substrates retained in our paper are single crystal of Al_2O_3 (sapphire, h = 500µm, ε_r = 10) and Lanthanum Aluminate ($LaAlO_3$, h = 500µm, ε_r = 24). These materials are usually used for the growth of KTN or BST films. The thicknesses of the ferroelectric (ε_{rf}, tanδ_f) and metallic conductors are labelled h_f and t, respectively. In this work, the tunable TL have been simulated using an 3-D commercial electromagnetic tools (Ansoft HFSS). The results obtained by HFSS have been validated by comparing them with data obtained analytically or by other simulators.

This paper is organized as follows. In section II, we investigate and discuss the tunability of various TL as a function of their characteristic impedance (Z_c), supporting substrate and gap dimensions (h & g) for the uni-planar structures. Their insertion loss and figure of merit are compared in section III. Finally conclusions are drawn in section IV.

II. Tunability of Planar transmission lines

The electrical characteristics of the TL represented in **Fig.1** (characteristic impedance Z_c, propagation constant γ) can be varied due to the non-linear bias electric field dependence of the dielectric permittivity of the ferroelectric film. Depending on the studied device, several definitions are available in the literature for the "tunability" [1, 5, 6]. In this work we adopt the following definition for the tunability *T* of planar TL:

$$T = Tunability(\%) = \frac{\varepsilon_{eff\ max} - \varepsilon_{eff\ min}}{\varepsilon_{eff\ max}} \times 100$$

where $\varepsilon_{eff\ max}$ and $\varepsilon_{eff\ min}$ are the maximum and minimum effective permittivity of the line, respectively. In this section, the dielectric and metallic losses are not taken into account.

2.1 – Influence of the line configurations

We compare the tunability of the three types of TL (**Fig.1**) at 10 GHz. These lines are printed on sapphire substrate coated with KTN films (h_f = 0.5 µm, 500 < ε_{rf} < 700). Targeting a characteristic impedance Z_c = 50 Ω for an average value of the ferroelectric permittivity ε_{rf} = 600, the TL dimensions become: a - MS TL) conductor width w = 436 µm ; **b** - CPW) w = 18 µm, gap width g = 30 µm ; **c** – CS TL) w = 310 µm, g = 30 µm. The gap width is maintained identical for CPW and CS configurations because it determines the DC-bias electric field corresponding to the tunable range of the ferroelectric material.

The variations of Z_c and ε_{eff} versus the ferroelectric permittivity are represented in **Fig. 2-(a)** and **(b)**. **Fig. 2-(a)** shows that, for all transmission lines, the impedance variations remain relatively small (less than ±2.5 Ω around 50 Ω). In particular for the MS line, the relative variation of Z_c is negligible (less than 1%); but the counterpart is a much lower relative variation of the effective permittivity (7.46 < ε_{eff} < 7.62 and T = 2% for the MS line) compared to the other two configurations (T = 16 %). Indeed, for the uni-planar configurations (CPW and CS), the RF electric field lines are concentrated within the gaps, whereas for the MS structure, they are mainly located in the substrate. In addition, as the magnitude of the DC-bias electric field is conversely proportional to the gap width, uni-planar configurations present roughly the same value of tunability. Finally, we can note that the average effective permittivity of the CPW TL (ε_{eff} = 14.3) is higher than that of the CS TL (ε_{eff} = 8.5). This can be explained by the ratio of their main conductors' width (w_{cpw} /w_{cs} = 0.058).

2.2 – Influence of the characteristic impedance

For each TL configuration, we investigated the variation of the tunability at 10 GHz for various values of Z_c (40, 50 and 60 Ω for ε_{rf} = 600). The dimensions of lines on a sapphire substrate are given in **Fig.3**. For all configurations, Z_c is controlled by the conductor widths.

The simulation results given in **Fig. 3** demonstrate that for MS and CS configurations, the tunability is almost constant (~ 2% and 15.2%, respectively) when Z_c increases from 40 to 60 Ω. The most promising results concern CPW transmission line for which the tunability increases by 20 % compared to its average value (T = 15.1 % for Z_c = 40 Ω and T = 18.3 % for Z_c = 60 Ω). This observation shows that, the tunability of CPW TL can be increased significantly by choosing high impedance lines.

2.3 – Influence of the substrate's permittivity

In this section we determine the influence of the supporting substrate on the tunability at 10 GHz. Two substrates are compared: (i) Sapphire: ε_r = 10, h = 500µm; (ii) Lanthanum aluminate ($LaAlO_3$): ε_r=24, h=500µm. MS, CPW and CS lines were designed to be matched at 50 Ω for ε_{rf} = 600. The numerical results given in **Fig.4** show that, for a given type of line, TL printed on $LaAlO_3$ substrates are less tunable that those on sapphire substrate. This decrease is quite important for uni-planar configurations, 23.5 % for the CPW structure (from 16.6 % on sapphire to 12.7 % on LAO) and 19 % for the CS configuration (from 15.2 % on sapphire to 12.3 % on LAO). This is due to the relatively high permittivity of LAO (ε_r=24) compared to sapphire (ε_r=10) which leads to a less effective concentration of the electric field in the ferroelectric layer.

2.4 – Influence of the gap width

For the uni-planar configurations (CS and CPW), we have studied the variation of the tunability at 10 GHz as a function of the gap width g. We assume that the TL are printed on sapphire substrates. The widths of the main conductors are given in section 2.1. The corresponding variations of T are represented in **Fig.5**. These results confirm that T increases as g decreases. Indeed, reducing the gap width leads to a more intense microwave electric field and thus an enhanced tunability. Moreover, the tunability of CPW is approximately 2 % higher than that of CS. Simulations have shown that, for CPW lines with a constant value of gap, a much wide main conductor (i.e lower Z_c) led to a slight decrease of the tunability, as seen in the section 2.2. Finally, we can note that when the gap width decreases (whatever the width of the main conductor is), the tunability of uni-planar lines tends to a limiting value which depends on the relative tuning range of the ferroelectric thin film (T_{ferro} = (700-500)/700 = 28.6 %)

III. INSERTION LOSS AND FIGURE OF MERIT

The comparative study of different configurations of TL requires determining their insertion loss that is a key parameter when designing tunable devices. In this Section we first investigate the variations of the insertion loss at 10 GHz as a function of the ferroelectric loss tangent **$\tan\delta_f$** and the gap width **g** for uni-planar configurations. Then we compare the global performance of the lines by defining their figure of merit. We assume that the metallic conductors are Aluminium ($\sigma=3.8\times10^7$S/m, t = 2 µm) and that they are printed on ferroelectric material ($\tan\delta_f$) coated on sapphire (ε_r=10, $\tan\delta=10^{-4}$).

3.1 – Influence of the ferroelectric loss tangent $\tan\delta_f$ on TL insertion losses

The dimensions (w, g) of the three lines are the same as those given in **Fig. 2**. Here we have changed the ferroelectric thin film $\tan\delta_f$ from 10^{-4} to 0.5 in order to study the variations of the TL insertion loss. **Fig.6** confirms that the overall loss increases exponentially with $\tan\delta_f$. In the MS case, the electric field is mainly concentrated in the substrate. Thus the ferroelectric losses compared to the total losses are less important than for uni-planar configurations and insertion losses remain relatively low (lower than 1.2 dB/cm). For the uni-planar configurations, a value of $\tan\delta_f$ smaller than 10^{-2} corresponds to constant insertion loss t: conductor losses are predominant. As $\tan\delta_f$ becomes higher than 10^{-1}, the insertion loss becomes crippling. For example, for a loss tangent of 0.5 it becomes higher than 6 dB/cm. In this case, the ferroelectric losses are predominant.

Fig.7-(a) and **Fig.7-(b)** show the individual contributions of metallic, ferroelectric and dielectric losses for two values of tanδ_f (10^{-3} and 10^{-1}), respectively. These two figures highlight several observations:

- Dielectric loss in the substrate: These losses are small for all configurations (lower than 0.2 dB/cm). However, due to the electric field pattern, the MS line has more substrate's loss (0.16 dB/cm) compared to uni-planar configurations (~ 0.1 dB/cm).
- Dielectric loss in the ferroelectric thin film: For tanδ_f ~ 10^{-3}, the ferroelectric losses are negligible (< 0.05 dB/cm) in the case of MS line and low for uni-planar lines (0.1 dB/cm). When tanδ_f is multiplied by a factor 100 (tanδ_f ~ 10^{-1}), ferroelectric losses increase rapidly (0.3 , 2.26 and 1.28 dB/cm for MS, CPW and CS lines, respectively). These losses represent for each line, more than 60 % of the global insertion loss. Moreover, the concentration of the electric field in both gaps rather than in only one gap, explains why ferroelectric losses in CPW are larger than in CS.
- Metallic loss: They are related to the inverse of the width of the main conductor. Thus, the CPW has the most important conductor loss (1.42 dB/cm) and the MS line the lowest loss (0.1 dB/cm). Conductor loss of CS lines is of the order of 0.5 dB/cm.

3.2 – Influence of the gap width in uni-planar configurations

The variation of the insertion loss is investigated as a function of the gap width g. The widths of main conductors are the same as those given in Section 2.1. According to **Fig.9** and as we would expected, the insertion loss increases exponentially when the gap width decreases: the ferroelectric losses increase with the electric field intensity in the gap.

3.3 – Definition of the figure of merit

To compare the different types of transmission lines, it is of primary importance to define a new criteria that takes into account both the tunability and the insertion loss (IL) and enables one to make a trade-off in terms between them. Here we define the figure of merit M as follows:

$$M(\%/dB) = \frac{T(\%/cm)}{IL_{max}(dB/cm)}$$

where IL_{max} represents the maximum value of insertion loss obtained when ε_{rf} varies. Here T is tunability determined for the lossless case. Several simulations have shown that the consideration of dielectric and conductor loss modifies only very slightly the value of T.

Fig.9 represents the variation of the figure of merit versus the gap width g. These results show that for g < 60 µm, the insertion loss increases more rapidly than the tunability. Thus, the figure of merit decreases with g and becomes smaller than that of the MS line (for g = 5 µm, M = 3, 4.35 and 5 %/dB for CPW, CS and MS configurations, respectively). For g > 60 µm, M increases up to a limiting value (15.5 and 8.7 %/dB for CS and CPW, respectively). This value corresponds to a tunability which decreases as slowly as the insertion loss. Let us note that for our range of gaps, the tunabilities of CPW and CS are of the same order of magnitude (**Fig.5**), whereas the insertion losses of the CPW configuration are about twice higher than that of the CS structure. Thus the figure of merit of CS is roughly double of that of CPW.

IV. CONCLUSION

We have compared in this paper the main properties of ferroelectric tunable transmission lines. Their characteristic impedance, tunability, insertion loss and figure of merit have been determined and compared. Our results have highlighted that uni-planar configurations offer a real potential of tunability: CS and CPW are much more tunable (T ~ 16 % for g = 30 µm) than the MS line (T ~ 1.55 %). Then we have shown that the figure of merit of CS configuration (M = 12.2 %/dB for g = 30 µm) is twice larger than that of CPW line (M = 6.3 %/dB for g = 30 µm). The numerical results given in this paper are of particular interest as preliminary data when designing reconfigurable devices. We should also mention that a technological prerequisite for large integration and development of ferroelectric tunable components is to reach a loss tangent of the order of 10^{-2}.

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FIGURE CAPTIONS

Fig. 1: Cross-section views of the three configurations of tunable Transmission lines (TL): microstrip line [(a), MS], coplanar waveguide [(b), CPW], coplanar strips [(c), CS]. w and g denote the width of the central conductor(s) and the width of the slot between conductors, respectively :

- ■ Electric conductors (t);
- ■ Ferroelectric thin film (h_f, ε_{rf}, $\tan\delta_f$);
- □ Substrate (h, ε_r, $\tan\delta$).

Fig. 2: Computed values of Z_c (a) and ε_{eff} (b) of MS line, CPW and CS at 10 GHz. Conductors and dielectrics are ideal. Substrate: ε_r = 10, h = 500 µm; Ferroelectric film: $500 < \varepsilon_{rf} < 700$, h_f = 0.5 µm.

- MS: w = 436 µm;
- CPW: w = 18 µm; g = 30 µm;
- CS: w = 310 µm; g = 30 µm.

Fig. 3: Variation of the effective permittivity ε_{eff} as a function of ε_{rf}, for three values of Z_c (ε_{rf} = 600) at 10 GHz. Conductors and dielectrics are ideal. Substrate: ε_r = 10, h = 500 µm; Ferroelectric film: 500 < ε_{rf} < 700, h_f = 0.5 µm.

MS: $Z_c(\varepsilon_{rf} = 600)$ = 40 Ω, w = 680 µm;

$Z_c(\varepsilon_{rf} = 600)$ = 50 Ω, w = 436 µm;

$Z_c(\varepsilon_{rf} = 600)$ = 60 Ω, w = 285 µm;

CPW: $Z_c(\varepsilon_{rf} = 600)$ = 40 Ω, w = 47 µm, g = 30 µm;

$Z_c(\varepsilon_{rf} = 600)$ = 50 Ω, w = 18 µm, g = 30 µm;

$Z_c(\varepsilon_{rf} = 600)$ = 60 Ω, w = 6 µm, g = 30 µm;

CS: $Z_c(\varepsilon_{rf} = 600)$ = 40 Ω, w = 1 mm, g = 30 µm;

$Z_c(\varepsilon_{rf} = 600)$ = 50 Ω, w = 310 µm, g = 30 µm;

$Z_c(\varepsilon_{rf} = 600)$ = 60 Ω, w = 100 µm, g = 30 µm.

Fig. 4: Variation of the effective permittivity ε_{eff} at 10 GHz of each TL as a function of ε_{rf}, for two substrates (sapphire and LAO, h = 500 µm). Conductors and dielectrics are ideal. Ferroelectric film: 500 < ε_{rf} < 700, h_f = 0.5 µm.

MS : /LAO, w = 140 µm;

/Sapphire, w = 436 µm;

CPW: /LAO , w = 6 µm, g = 30 µm;

/Sapphire, w = 18 µm, g = 30 µm;

CS: /LAO, w = 70 µm, g = 30 µm;

/Sapphire, w = 310 µm, g = 30 µm.

Fig. 5: Tunability of the uni-planar TL versus gap width g. Conductors and dielectrics are ideal. Substrate: sapphire, ε_r = 10, h = 500 µm; Ferroelectric film: $500 < \varepsilon_{rf} < 700$, h_f = 0.5 µm. 5 µm < g < 100 µm.

CPW: w = 18 µm;

CS: w = 310 µm.

Fig. 6: Variation of the insertion losses of TL at 10 GHz as a function of the loss tangent $\tan\delta_f$ of the ferroelectric film. Conductors: $\sigma = 3{,}8\times10^7$ S/m (Aluminium), t = 2 µm; Substrate: sapphire, ε_r = 10, $\tan\delta = 10^{-4}$, h = 500 µm; Ferroelectric film: ε_{rf} = 700, $10^{-4} < \tan\delta_f < 5\times10^{-1}$, h_f = 0.5 µm. The values of (w, g) are those given in **Fig.2**.

MS;

CPW;

CS.

Fig. 7: Contribution of different losses for each TL at 10 GHz. Conductors: $\sigma = 3{,}8\times10^7$ (Aluminium), t = 2 µm; Substrate: sapphire, ε_r = 10, $\tan\delta = 10^{-4}$, h = 500 µm; Ferroelectric film: ε_{rf} = 700, $\tan\delta_f = 10^{-3}$ (**Fig.8-(a)**) and $\tan\delta_f = 10^{-1}$ (**Fig.8-(b)**), h_f = 0.5 µm. (w, g) for lines are those given in **Fig.2**.

■ Conductor loss;

■ Ferroelectric loss;

□ Dielectrics loss in the substrate.

Fig. 8: Variation of the insertion losses of TL at 10 GHz as a function of the gap width g. Conductors: $\sigma = 3{,}8\times10^{7}$ (Aluminium), t = 2 µm; Substrate: sapphire, $\varepsilon_r = 10$, $\tan\delta = 10^{-4}$, h = 500 µm; Ferroelectric film: $\varepsilon_{rf} = 700$, $\tan\delta_f = 5\times10^{-2}$, $h_f = 0.5$ µm. 5 µm < g < 30 µm.

CPW: w = 18 µm;

CS: w = 310 µm.

Fig. 9: Variation of the figure of merit of TL at 10 GHz as a function of the gap width g. The figure of merit of MS lines has been included for comparison purposes. Conductors: $\sigma = 3{,}8\times10^{7}$ (Aluminium), t = 2 µm; Substrate: sapphire, $\varepsilon_r = 10$, $\tan\delta = 10^{-4}$, h = 500 µm; Ferroelectric film: $\varepsilon_{rf} = 700$, $\tan\delta_f = 5\times10^{-2}$, $h_f = 0.5$ µm. 5 µm < g < 30 µm.

MS: w = 436 µm;

CPW: w = 18 µm;

CS: w = 310 µm.

FIGURES

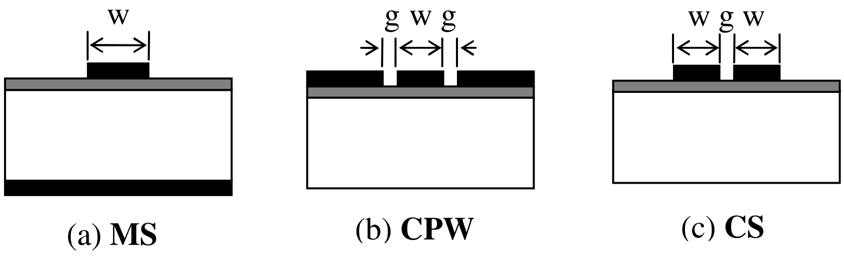


Fig.1

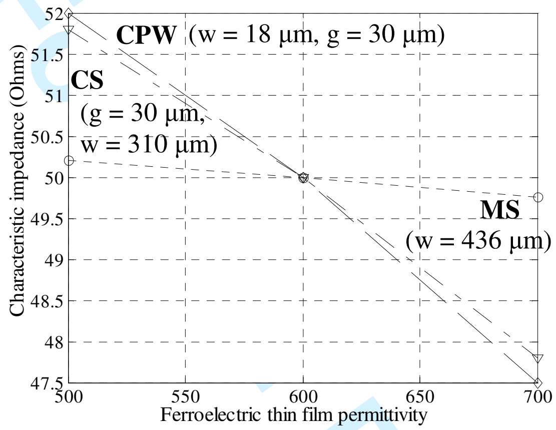
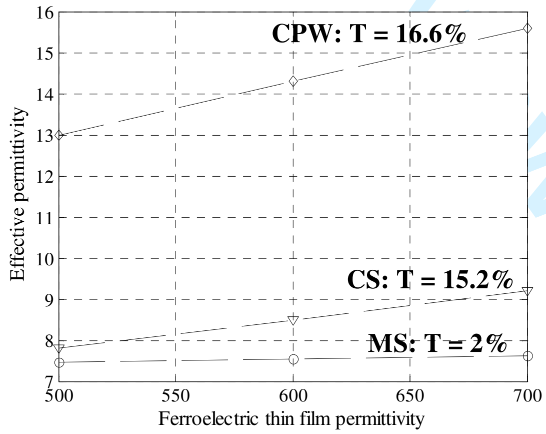


Fig.2-(a)



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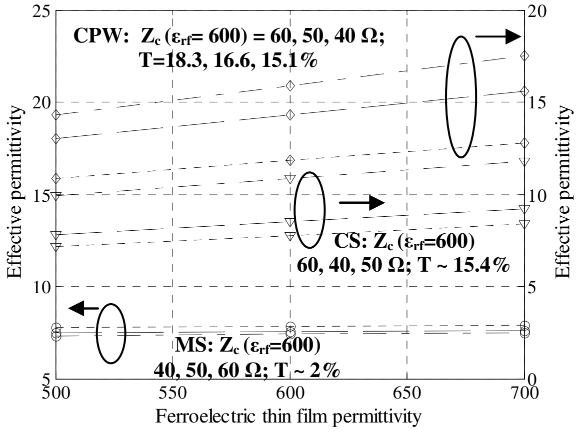

Fig.3

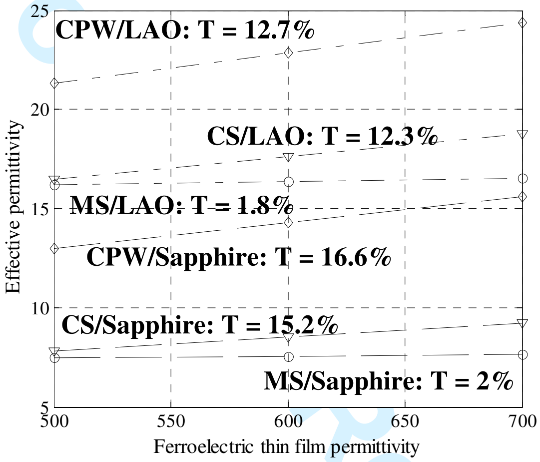

Fig.4

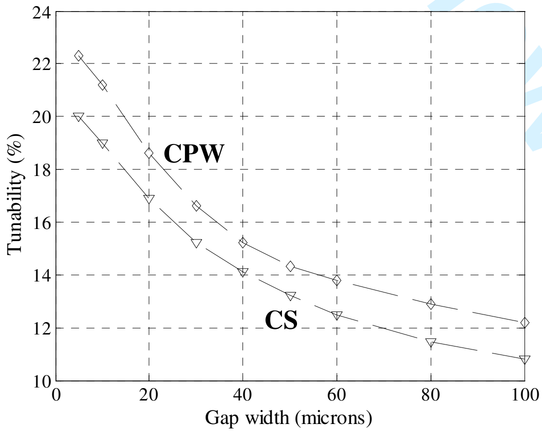

Fig.5

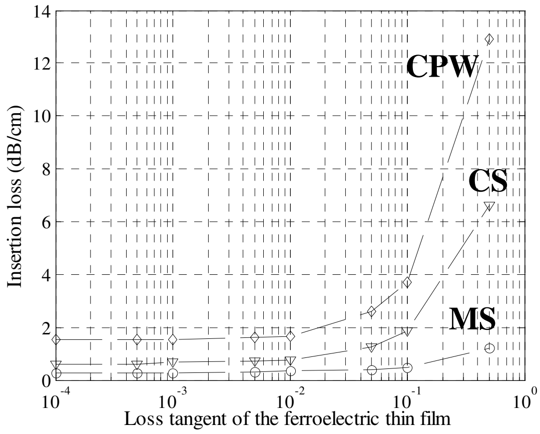

Fig.6

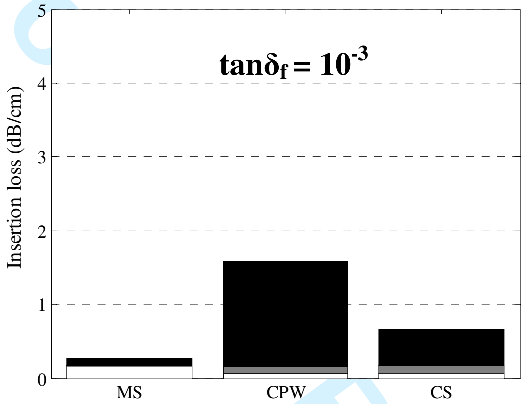

Fig.7-(a)

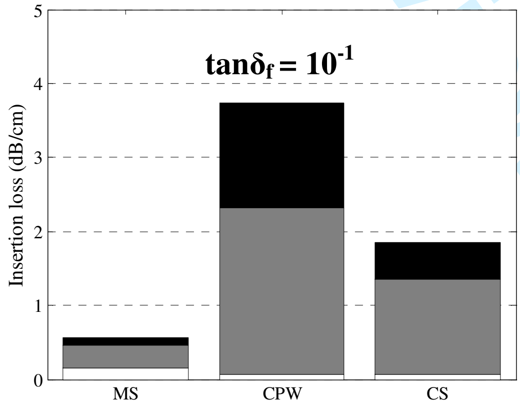

Fig.7-(b)

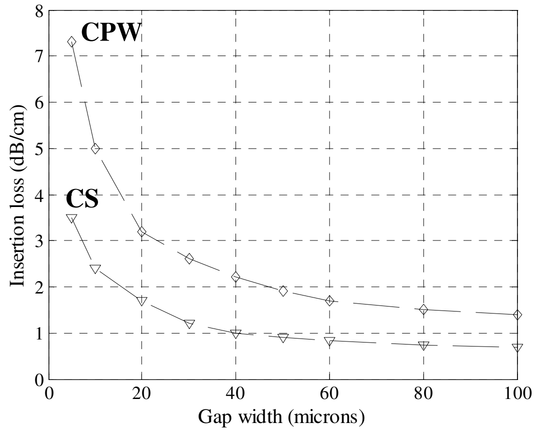
CPW
CS
Insertion loss (dB/cm)
Gap width (microns)
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100

Fig.8

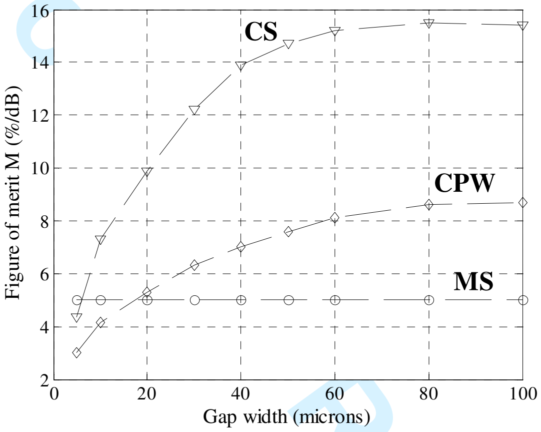
CS
CPW
MS
Figure of merit M (%/dB)
Gap width (microns)
2
4
6
8
10
12
14
16
0
20
40
60
80
100

Fig.9