Designing of High-Q Slow-Wave Coplanar Strips for CMOS MMICs

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Abstract—In contrast to conventional coplanar transmission lines, slow-wave coplanar transmission lines offer higher quality factor and smaller on-chip area. Among coplanar transmission lines, coplanar strips have the advantage of higher level of integration and a balanced structure that has favourable features for integrated voltage controlled oscillators (VCO) and low noise and power amplifiers. In this article, the affect of geometrical dimensions of slow-wave coplanar strips on the quality factor, characteristic impedance, and on-chip wavelength are investigated. Based on the presented guidelines mm-wave slow-wave coplanar strips operating at 60 GHz in a standard CMOS process were optimised for a 50 Ω characteristic impedance with a 250% improvement in quality factor of 31.

I. Introduction And Background

Despite of some drawbacks, such as low-resistivity substrate of current CMOS processes, they still promise higher levels of integration at low cost. Furthermore, using silicon technologies, mm-wave CMOS circuits directly benefit from the higher speed of technology scaling [1]. With CMOS transistors scaling to down to sub-100 nm, intrinsic frequency has increased dramatically, making this technology very attractive for circuits operating at microwave and mm-wave frequencies. This was driven by the increased market demand for low-cost electronics that operate at the 60 GHz license-free band. To effectively exploit modern silicon CMOS processes in mm-wave frequencies, on-chip high quality factor passive components are required [2, 3]. Among these passive components, coplanar transmission lines (CPTLs) play a critical role because they explicitly take into account the distributed behaviour. n contrast to other types of transmission lines, coplanar transmission lines have the advantage of lower resistive loss, they typically suffer from conductive loss in a silicon process [4]. This conductive loss is mainly due to the penetration of the electric field of the CPTL into the low resistivity silicon substrate [5]. Placing an array of closely spaced narrow floating strips under the coplanar transmission line (slow-wave transmission line) is one effective method of reducing the substrate loss, allowing for a high-Q transmission line implementation [6]. In contrast to the solid metal shield, if the floating strips are narrow enough, eddy current loss is negligible. Therefore the shield, effectively reduces the substrate loss and it does not add considerable eddy current loss [7].

Figure 1 shows a slow-wave coplanar strips structure (SCPS). The floating strips in this structure not only act as a shield but also reduces the propagation velocity of the electromagnetic wave, hence the name. Slow wave transmission line structures are essentially structures with spatially separated electric and magnetic energy storage. So in SCPS it is possible to increase *L* and *C* simultaneously and so reduce the wave propagation velocity [8]. For instance in Figure 1, the line inductance is not affected by the floating strips, while the shield strips add parasitic capacitance between the two traces of the transmission line and consequently reduces the wave propagation velocity.

Considering the wavelength as the ratio between velocity and frequency reveals another important feature of the slow-wave coplanar transmission lines in mm-wave integrated circuits design, which is the reduction of the propagation speed, resulting in reducing the effective wavelength [7]. Therefore, transmission line with smaller physical dimensions can be implemented on-chip, resulting in an effective utilisation of silicon area [6, 9].

Coplanar strips have the advantage of higher level of integration and a balanced structure that have favourable features for integrated voltage controlled oscillators (VCOs) and low noise and power amplifiers[10]. Although a number of studies presented slow-wave coplanar waveguides [6, 11], design guidelines for slow-wave coplanar strips are not available. In the following section guidelines for slow-wave CPS based on full wave 3D electromagnetic simulation are presented.

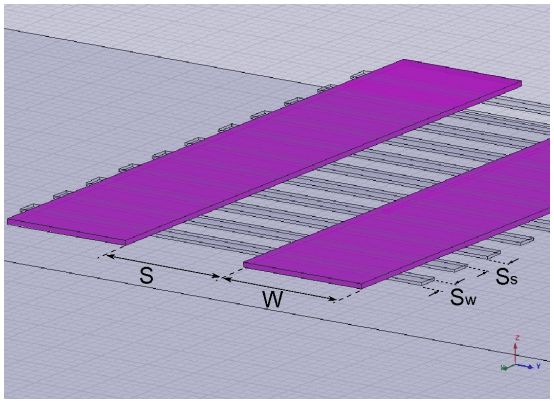

Fig.1. Slow-wave coplanar strips structure.

II. Guidelines

In this section the affect of geometrical parameters on the quality factor, characteristic impedance, and wavelength of the propagated electromagnetic wave are investigated and design guidelines based on 3D modelling of the structure are given. A summary of these guidelines are:

(1) For a specific value of spacing between conductors (S), the transmission line has the maximum average stored energy, hence a maximum quality factor. On the other hand, for spacing values less than the specific value, the inductance per unit length of the line is small, so the inductive quality factor reduces the total quality factor of the line. Furthermore, for values greater than the spacing specific value, capacitance per unit length of the line is small; hence capacitive quality factor reduces the total quality factor of the line.

(2) For small values of *W*, the quality factor is low. As *W* increases the quality factor increases till it reaches a peak and then decreases again. This behaviour can be explained with the

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effect of W on resistance, conductance, capacitance and inductance of the line. Low values of W leads to higher values of inductance and lower values of conductance, but it also increase the resistance and decrease the capacitance of the line. On the other hand, although, a wide line has low resistance and high capacitance, it also has high conductance and low inductance.

So, there is a specific point in the 2D space of W and S at which a conventional CPS has a maximum quality factor.

(3) The results show that Q-factor of the S-CPS is increased when decreasing the width of the floating strips (S_w). The best Q-factor can be achieved for the narrowest floating strips that are available by the design rules of the process. This can be explained by considering that wider floating strips result in more eddy current loss in the shields.

(4) The results also show that the spacing between floating strips (S_s) does not have a significant effect on Q-factor. However, such spacing reduces the on-chip wave length of the propagating wave. Thus, depending on the design expectations, designer can adjust the period of floating strips to have a maximum Q-factor or the minimum on-chip wave length.

III. Results

In this work, using full wave electromagnetic simulations, the effect of geometrical dimensions of a conventional coplanar strips (CPS) and slow-wave coplanar strips (S-CPS) on quality factor were investigated. Design guidelines for high quality slow-wave CPS in CMOS MMICs are presented. The narrowest floating strips available in a process can be used to achieve the maximum Q-factor. Also, reducing the floating strips spacing (S_s) results in smaller on-chip wavelength, but it does not result in a maximum Q-factor of the S-CPS. Furthermore, although adding floating strips to a conventional CPS, which is designed for maximum Q-factor results in smaller on-chip area, but this is not the maximum achievable quality factor of a slow-wave CPS. Consequently to achieve the maximum quality factor of the slow-wave CPS a search using 3-dimensional space of S, W and S_s should be conducted.

By using the presented design guidelines, a quarter wavelength slow-wave coplanar transmission line with S = 25 µm, W = 20 µm, S_w = 0.2 µm and S_s = 2.2 µm at 60 GHz is simulated and its properties are compared with those of a quarter wave length optimum conventional CPS with S = 6 µm and W = 6 µm. Although the S and W of the S-CPS are much larger than those of the conventional CPS the total on-chip areas of both S-CPS and conventional CPS are almost equal (1300 µm^2 for S-CPS and 11200 µm^2 for conventional CPS). That is because, on-chip wave-length of the propagating wave for S-CPS is 800 µm but for conventional CPS it is 2500 µm. However, the aspect ratio of these lines is significantly different from the conventional counterpart, leading an efficient utilisation of silicon area.

As shown in Figure 1, the quality factor of the S-CPS is 31, in contrast with the maximum Q-factor of the conventional CPS which is less than 12. This is a significant improvement in the Q-factor by 250%. Furthermore, using S_w and S_s of the floating strips as two extra degrees of freedom for adjusting the properties of the transmission line, a characteristic impedance near 50 Ω is achieved for S-CPS, while the characteristic impedance for the optimum conventional CPS is greater than 100 Ω.

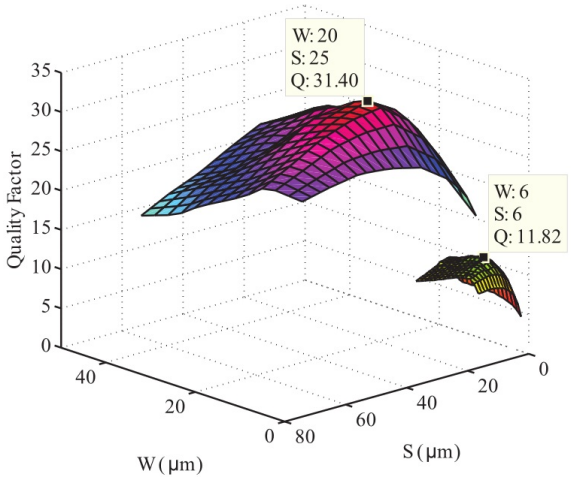

Fig.2. Simulation results for the quality factor of both optimum slow-wave coplanar strips and conventional coplanar strips at 60 GHz. Simulation results show a maximum Q-factor of 31.4 for slow-wave CPS with W = 20 µm and S = 25 µm.

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