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Review

A review on quality factor enhanced on-chip microwave planar resonators

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ABSTRACT

This paper reviews microwave on-chip resonators with emphasis on quality-factor (*Q*-factor), and techniques enhancing *Q*-factor. The review discusses both planar microstrip and waveguide structures, with the integration of the latter emerging as a substitute for the bulky and expensive non-planar waveguides. Despite their huge *Q*-factor the conventional waveguide does not support integration and miniaturisation. While the microstrips support miniaturisation and mass fabrication at low-cost, they are limited by low *Q*-factor due to high conductor and substrate losses. A study of *Q*-factor enhancing techniques for on-chip devices is presented, with an introduction of integrated waveguide structures. In addition, a summary of transitions between on-chip planar microstrips and planar waveguides is presented.

Contents

1. Introduction

The demand for portable and efficient wireless devices prompts the need for integrated circuits of high quality (*Q*-factor), for high level integration at high frequencies. These circuits include planar microstrip resonators [1] and planar integrated waveguide [2]. Despite the advantage of small circuit size and high integration density [3,4], planar resonators suffer huge transmission loss due to conductor and substrate losses [5,6]. However their application to microwave and millimetre-wave frequency is unavoidable, thus instigating research in loss reduction mechanisms to improve *Q*-factor and circuit performance. Consequently, various loss reduc-

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tion [7] and Q-enhancement [8] methods were presented in previous works and some of those techniques are discussed in subsequent sections of this paper.

1.1. Overview of microstrips

Integrated transmission lines (microstrips) are the most fundamental elements in the design of low-cost miniaturized microwave circuits [9] such as filters and antennas. For many years microstrip circuits were used for filtering application at lower frequencies in the radio frequency (RF) range. These circuits gained popularity with the advantage of low-cost, easy fabrication, planar nature and ability to integrate with solid-state devices. Even with the above mentioned advantages, the circuit experience excessive conductive and magnetically induced losses [10]. While radiation and dielectric losses are also significant, ohmic losses due to lossy substrate and metal traces are the two main contributors to the overall losses of the circuit. This leads to very low Q-factor for on-chip elements compared to their off-chip counterparts. Enormous advancement in research on the performance trends, modelling and design [11–14], optimisation and Q-factor enhancement methods of microstrip circuits and substantial results are reported [8,15–17] for various RF applications. Some of these techniques are introduce and discuss in Section 2 of this manuscript.

1.2. Overview of substrate integrated waveguide

Substrate Integrated Waveguide (SIW) [18–21] technology emerged in the last two decades as an alternate design of resonant structures for microwave and millimetre-wave applications. These are substrate integrated circuits (SICs) [22] made-up of double rows of conducting slots immersed in a dielectric substrate that connects two plates on either side of the substrate. Like the microstrip structures, they are affected by conductor, radiation and dielectric losses [23] limiting their performance. Despite losses related to conductor and substrate materials, the SIWs possess the characteristics of a rectangular waveguide such as high Q-factor and low radiation loss with an extra advantage of reduced size by a factor of $\varepsilon^{1/2}$ [24] to the original size. In addition, the unloaded Q-factor of SIWs is much greater than that of microstrip circuit [19], therefore these are fundamental components for high frequency ICs. Some SICs are a combination of SIW and a microstrip in what is normally as a hybrid integration [25]. The application of the SICs to high frequency devices provide an alternate solution to high performing circuits with complementary advantages of microstrips and waveguide circuits [26]. Several publications introduce and discuss these structures, and a summary is presented on Section 3 of this manuscript.

1.3. Quality-factor

As a figure of merit, Q-factor determines the performance of any resonant structure. It is defined as the ratio of energy stored to the total energy lost per cycle for a sinusoidal excitation. Q-factor is described by (1) as in [27],

$$Q = 2\pi \frac{Energy\ stored}{(energy\ lost\ per\ cycle)} \tag{1a}$$

$$= 2\pi \frac{E_{mag,max} - E_{elec,max}}{P_{avg}} \tag{1b}$$

Where $E_{mag,max}$ and $E_{elec,max}$ are the maximum magnetic and electric energy respectively, and P_{avg} is the average power dissipated. Eqs. (1a) and (1b) show that Q-factor is highly dependent on the amount of energy lost per cycle. An increase in energy loss results in low Q-factor prompting the need for Q-enhancement mechanism. Despite several Q-enhancing techniques reported [2,9,25,28,29] it is difficult to achieve high Q-factor in planar structures. An investigation on the state-of-the-art progress in Q-enhancement is discussed in this paper.

The paper is structured as follows: Section 1 – provides a general introduction to on-chip and substrate integrated resonators, Section 2 – analyses on-chip microstrip resonator and Q-enhancement methods, Section 3 – analyses substrate integrated waveguide with Q-factor consideration, Section 4 – reviews hybrid integration of conventional planar structures to non-planar structures on a single substrate, and Section 5 – reviews substrate material properties and effect on resonator performance.

2. Microstrip analysis

In its simplest form, a microstrip resonator consists of two metal conductors separated by a dielectric substrate as illustrated in Fig. 1. The suspended metal trace on the substrate is a strip-line whereas the underneath metal plate is a ground plane.

Microstrip lines are used to develop inductors in various shapes as presented by Fig. 2. An inductor with least number of sides is square spiral [31,32], while the one with infinite number of sides

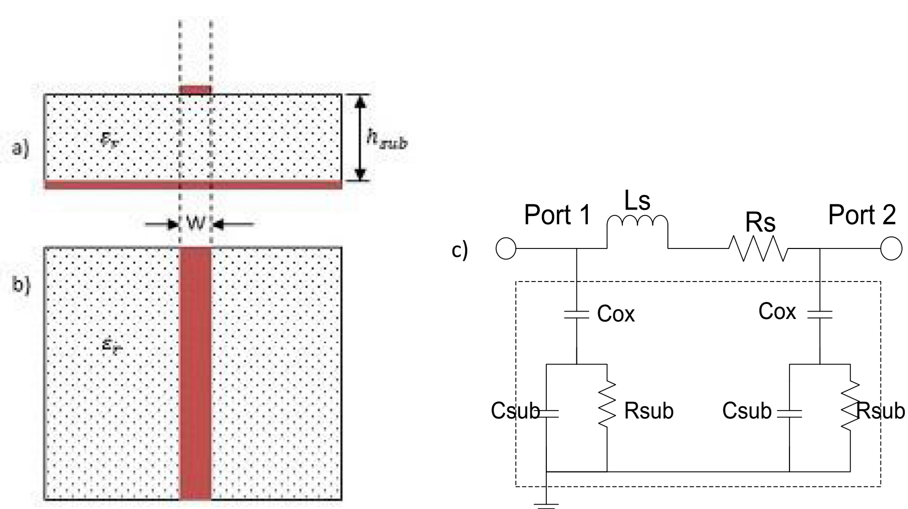

Fig. 1. Microstrip geometry a) side-view, b) top-view, and c) equivalent lump circuit [30].

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