A Novel Substrate Integrated Coaxial Line (SICL) for Wide-Band Applications

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***Abstract*— A novel substrate integrated coaxial line (SICL) is presented and experimentally verified in this paper. This structure exhibits unimodal operation over a wide frequency band, is shielded and not dispersive, can be fabricated by using simple, low-cost thin–film process, and can be easily integrated with active devices. Moreover, the same technology results particularly suitable to realize passive components for wideband applications. The design of a Lange coupler with operation bandwidth of 66%, to be used in a Multi-port Impulse Radio for Ultra Wide Band applications, is reported.**

***Index Terms*— Hybrid coupler, substrate integrated circuits, ultra wide band.**

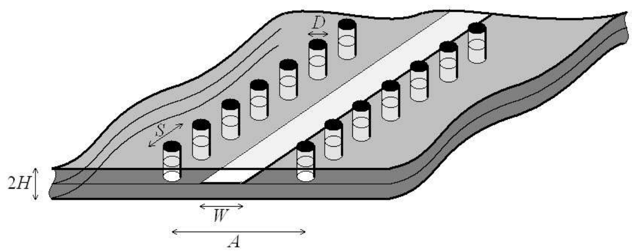


Fig. 1. Geometry of a Substrate Integrated Coaxial Line.

I. Introduction

Many novel applications in the microwave and millimeter wave range require components operating over a wide frequency band [1]. The basic passive component for any microwave system is represented by the transmission lines. To meet the requirements of wide-band systems, transmission lines should guarantee unimodal operation over a wide frequency range. Moreover, the propagation of the fundamental mode should be not dispersive, to avoid the distortion of the propagating signal. Another important feature which should be accounted for is the possibility of avoiding interference between adjacent lines (especially in densely integrated devices). Therefore, shielded structures should be preferred. The possibility of fabricating such lines and the associate components by using a standard technology available at a low cost represents a key–point, especially for mass production and consumer electronics. Finally, in order to realize complete systems with the same technology, the possibility of easily integrating transmission lines and passive components with active devices is of paramount importance.

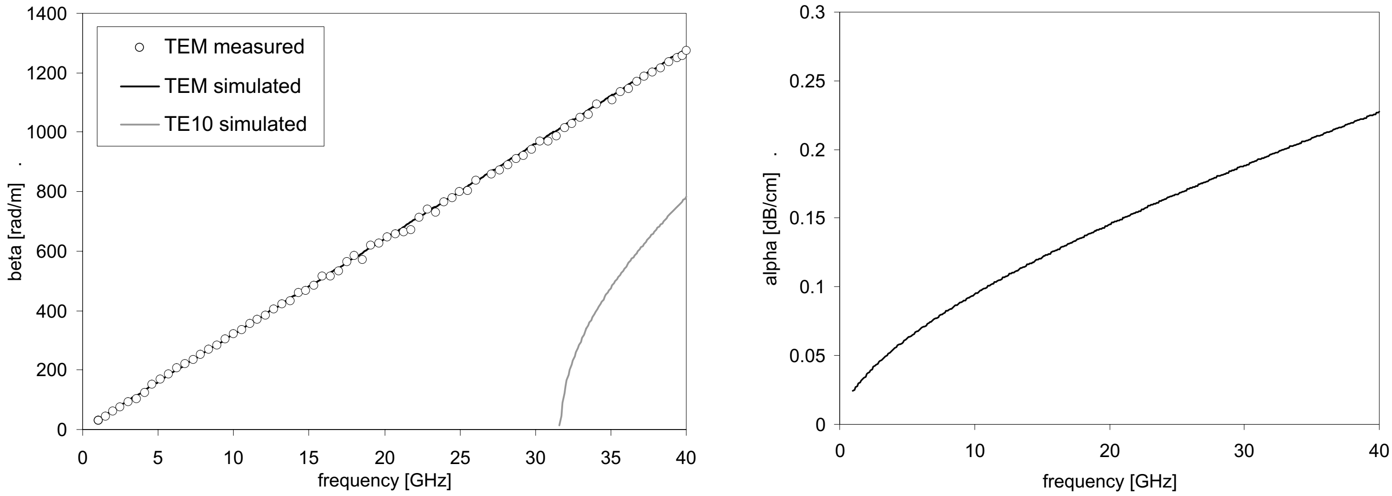
Among the commonly used transmission lines, coaxial cables are not dispersive and shielded, but cannot be integrated on a dielectric substrate, due to their geometry. Microstrip lines are easy and cheap to fabricate, but are not shielded and presents problem of loss due to radiation and cross-talk issues. Strip lines, on the other hand, present the issue of lateral leakage as well as cross-talk problems. In the recent years, substrate integrated waveguides (SIW) and substrate integrated slab waveguides (SISW) have been proposed [2], [3]. Even though such technologies are very suitable to full system integration on the same dielectric substrate and can be fabricated by standard and cheap processes, these transmission lines are dispersive, and therefore not particularly suitable for wideband applications.

This paper presents a novel transmission line, named the Substrate Integrated Coaxial Line (SICL), which consists of a printed coaxial structure, laterally shielded by metallized holes (Fig. 1). This structure combines the advantages of the coaxial cables and of the planar transmission lines. In fact, it presents unimodal operation over a wide frequency band, is shielded and not dispersive, can be fabricated by using simple, low-cost thin–film process or by CMOS technology, and can be easily integrated with active devices.

The design criteria of a SICL are discussed in Sec. II, and the fabrication and testing of a prototype operating up to 32 GHz are reported in Sec. III. Moreover, the application of this technology to a fully integrated wide–band hybrid coupler for Multi-port Impulse Radio for Ultra Wide Band applications is discussed, and the design of a Lange coupler is presented in Sec. IV.

II. Substrate Integrated Coaxial Line (SICL)

Substrate Integrated Coaxial Line is a planar coaxial transmission line, comprising a conductive thin film sandwiched



a *b*

Fig. 2. Dispersion diagram of the measured SICL compared to the simulated one

between two grounded dielectric layers and side-limited by two rows of metallic via holes (Fig. 1). Similarly to a strip line, the SICL allows the propagation of a TEM mode. The lateral shielding due to the metallic holes avoids the propagation of the unwanted parallel–plate mode, which could be excited by any discontinuity, causing leakage and interferences with other lines.

The first upper mode of the SICL is the TE_{10} mode. It exhibits the same propagation properties of a Substrate Integrated Waveguide [2], since the central conductor does not affect its modal field structure. Therefore, as derived in [4] under some hypotheses, the cut-off frequency of TE_{10} mode can be found by using the following formula

$$f_{TE10} = \frac{c}{2\sqrt{\epsilon_r}} \left(A - \frac{D^2}{0.95S} \right)^{-1} \quad (1)$$

where A, D and S are dimensions shown in Fig. 1, ϵ_r is the relative dielectric permittivity, and c is the speed of light in vacuum. Since D and S are usually imposed by technological constraints (as discussed later), f_{TE10} and, consequently, the unimodal bandwidth of the line, can be controlled by adjusting the distance A between the two rows of holes. This permits to achieve a very broad unimodal operation bandwidth, much wider than in similar planar structures as SIW.

The characteristic impedance Z_0 of the TEM mode is frequency independent. In the design process, its value can be adjusted by playing with the ratio between the height of the structure ($2H$) and the width of the inner conductor (W).

In conclusion, the SICL presents the same characteristics of a coaxial line, since it is a shielded and not-dispersive TEM propagating structure. The main advantages over coaxial lines is that SICLs can be realized with a simple thin–film process, usually adopted for planar circuits, and can be easily integrated with active devices.

III. DESIGN AND TESTING OF AN SICL

An SICL has been designed for unimodal operation up to 32 GHz. To this aim, according to (1), dimension A has been set to the value 3.55 mm. Since the height has no influence on the propagation properties of the line, it was set to $2H = 0.5$ mm for fabrication convenience. In order to achieve characteristic impedance $Z_0 = 50\ \Omega$, the width of the inner conductor has been optimized to the value $W = 0.4$ mm. The diameter of each metallized hole and the spacing between them were imposed by technological constraints, and their values are $D = 0.75$ mm and $S = 1.25$ mm, respectively.

This structure has been simulated by using the commercial Finite Element Method (FEM) software Ansoft HFSS (release 9.0), to determine its propagation and attenuation constant versus frequency (Fig. 2). As shown in Fig. 2*a*, the propagation constant of the TEM mode presents a linear dependence on frequency, and the cut–off frequency of the first upper mode is 32 GHz. Moreover, considering the value of losses shown in Fig. 2*b*, it is observed that the losses of SICL are acceptable for many applications and are comparable with other planar structures.

A prototype of this SICL has been fabricated by using a standard thin-film process. Two layers of dielectric substrate Rogers RT/Duroid 5870 ($\epsilon_r = 2.33$) with thickness $H = 0.25$ mm have been used. On the bottom layer a copper film line was created by etching process. The top layer was then aligned and stuck with the bottom one. Finally two rows of metallic holes were drilled and metal rivets posted. To measure the SICL by using a test fixture connected to the Vector Network Analyzer (VNA), an offset of 1.25 mm on both ends of the upper layer was realized, to provide the step necessary for connection with the test fixture.

In order to measure the propagation characteristics of the

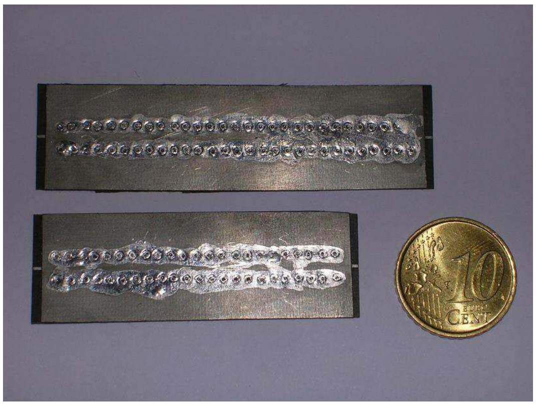


Fig. 3. Picture of two SICL lines fabricated

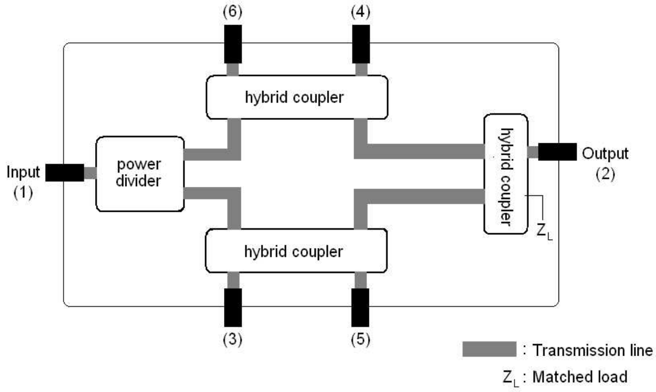


Fig. 4. Scheme of a six-port modulator.

TEM mode by using the multi-line method described in [7], two identical lines with different length have been fabricated (the longer is 62.5 mm, the shorter is 51.75 mm, see Fig. 3). After measuring the scattering parameters of both lines, the multi-line method has been applied to determine the propagation constant β, deembedding any effect of discontinuities caused, for instance, by test fixture and cables' imperfections. Fig. 2*a* shows the excellent agreement between simulation and measurement results, in terms of propagation constant over the whole measured frequency range.

IV. Application to a Lange coupler

Substrate Integrated Coaxial (SIC) technology has been proved to be particularly suitable for those systems that require wide-band and not-dispersive properties. In the project of a Multi-port Impulse Radio (MIR) for Ultra Wide Band (UWB) applications between 3 and 10 GHz [5], six-port circuits have been adopted as modulator and demodulator. The scheme of the six-port modulator is shown in Fig. 4. In the current implementation of MIR, standard commercial components have been used (in particular, hybrid couplers that present a narrow coupling band.) In this circuit, the overall system bandwidth is limited by the hybrid couplers, which exhibit a 3 ± 0.5 dB–bandwidth of 400 MHz.

To considerably improve the performance of the whole system, a wide-band Lange coupler has been designed in SIC technology (Fig. 5). The simulation code Ansoft HFSS has been used to perform the design. The coupling is provided by 8 interdigitated lines, properly connected by means of interconnecting film conductors and small metallic holes (as detailed in Fig. 5*b*). The width of each coupling line is 0.25 mm and the diameter of interconnecting holes is 0.125 mm. The spacing between two fingers is 0.15 mm, which represent the minimum distance allowed by the available technological process. The structure can be realized by double-side processing of a thin substrate (0.125 mm), sandwiched by two thick substrates in the same material (Rogers RT/Duroid 5870). The width of the port lines is chosen in order to obtain 50 Ω characteristic impedance. Finally, metallic holes have been added both in the line and coupling region, thus shielding the whole structure.

The simulation results of the scattering parameters are shown in Fig. 6. The required amplitude unbalance of ± 0.5 dB is achieved in the frequency band from 2.2 to 4.8 GHz, corresponding to a relative bandwidth of 74%. Over this whole band, both matching and isolation are larger than 13 dB. Phase shift of the through ($\angle S_{41}$) and coupled ($\angle S_{21}$) paths are presented in Fig. 6*b*. The required phase unbalance of ± 5 degrees is achieved in the frequency band from 2 to 4.4 GHz. Therefore the bandwidth useful for the application is from 2.2 to 4.4 GHz (66%).

In conclusion, this coupler represents a good alternative to Lange couplers already presented in the literature, since the use of bonding wires are avoided for a totally integrated and shielded structure. Moreover, this coupler exhibits superior performance in terms of bandwidth over other solutions, such as branch line couplers or broadside-coupled lines, or even directional couplers realized in SIW technology [6].

V. Conclusion

An innovative Substrate Integrated Coaxial Line (SICL) has been presented as a shielded, not-dispersive, wide-band planar transmission line. This new line is very compact and low-cost at low frequencies for UWB, and is suitable for applications at millimeter–wave frequencies.

The prototype of an SICL has been designed, fabricated, and tested over a wide frequency range.

A fully integrated Lange coupler has been designed in substrate integrated coaxial technology, which finds application in the recently proposed Multi-port Impulse Radio for application in ultra-wide band system. The simulation of the coupler showed outstanding performance, with a useful bandwidth of 66%, well superior over commonly used couplers.

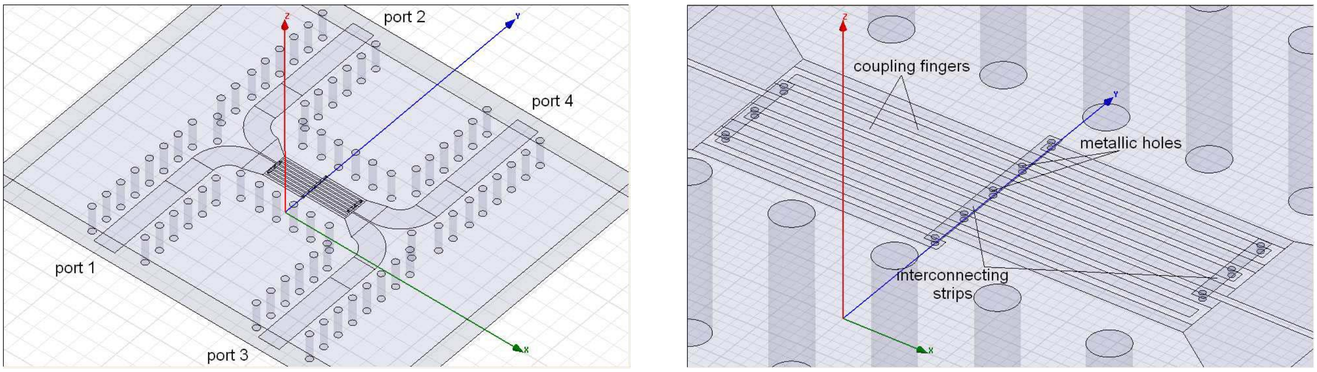


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Fig. 5. Layout of the Lange coupler in SIC technology: *a* overall view; *b* detail of the interdigited region.

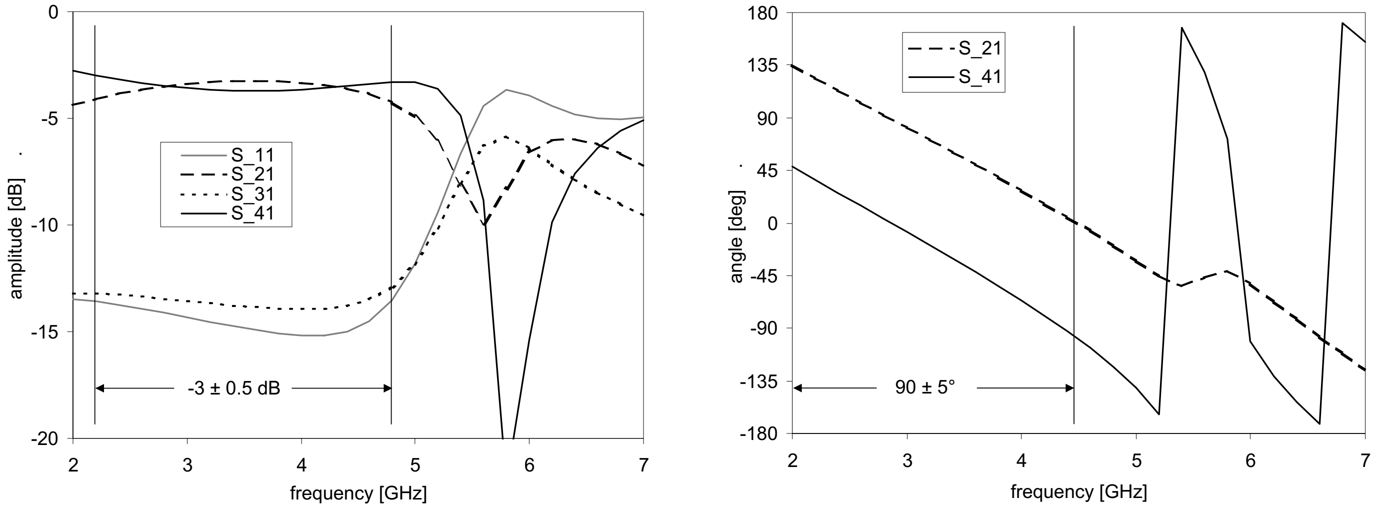

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Fig. 6. Scattering parameters of the Lange coupler designed in SIC technology, simulated with HFSS: *a*) amplitude of the S–parameters; *b*) phase of S_{21} and S_{41} parameters.

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