Integrated Waveguides for Ultra-High Speed Interconnects

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ABSTRACT

Integrated circuit technology is causing system designs to move towards complex architectures, requiring communication channels characterised by ever increasing capacity. In this context, classical metallic interconnects become a bottleneck, owing to the power consumption, crosstalk and signal integrity issues. Integrated Substrate Waveguides (SIW) are a potential technological solution to overcome traditional interconnect limitations. In the paper the Authors present frequency and time domain analysis of these structures, comparing two different SIW structures in terms of time and signal dispersion performances.

Keywords

Integrated Substrate Waveguides, High Speed Interconnects, Integrated optics.

1. INTRODUCTION

Integrated Circuit (IC) technology is causing on-chip and intra-chip communication to become, without doubt, the most important issue in the design of high performance complex systems. In current PCBs, for example, shared parallel buses are already being replaced by high-speed point-to-point serial buses to obtain reduced power consumption and most of all to eliminate timing and clock skews. On the other hand, because of the continued growth of the clock frequency of microprocessors, the bandwidth required by new-generation microprocessors and chipsets is increasing sharply.

A similar issue arises for modern FPGAs, as available I/O interfaces provide high throughput using serial signalling rates up to 10 Gb/s [1]. Serial signalling has significantly reduced the number of traces and connections within the system, but it has created new challenges for designers.

Traditional interconnects are realised by using copper-based-alloy wires surrounded by dielectric material to transmit an electrical signal. As is well known, this kind of interconnect tends to exhibit very high RC time constants, which increases the interconnect delay, thus reducing overall system speed. Moreover, they are characterised by significant signal degradation, power dissipation, and electromagnetic interference, all phenomena that increase with clock speed.

Optical interconnects, by replacing electrical wires with faster optical waveguides, were believed to be a solution to the communication bottleneck [2]. However, the use of optical interconnect technology still proves extremely disadvantageous mainly because of the number of fabrication steps and of the materials required, which are more expensive than those normally used in present manufacturing processes [3].

Integrated Waveguides (IW) are newly introduced waveguiding structures that can be manufactured using conventional printed circuit or IC technology. The IW inherits the advantages of the conventional metallic waveguide, such as high Q-factor and high power capacity, and at the same time can be easily integrated into planar circuits. Moreover, the absence of crosstalk phenomena and low losses may actually made them a suitable candidate for the high-speed/high-frequency digital signalling.

Recently, substrate integrated waveguides (SIW) have been studied and proposed as pursuable interconnects owing to their low cost and perfect compatibility with traditional fabrication processes for both ICs and PCBs.

The results presented in [4], where the characteristics of an SIW based serial link were investigated, show that these structures can support high-speed data transmission. However, the proposed waveguide presents some drawbacks. First, efficient transitions are needed in order to be integrated with planar circuits [4]. Moreover, the bandpass of this structure does not include low frequencies. As a consequence, ad-hoc drivers and receivers have to be used to accommodate baseband transmission [4], thus increasing power consumption and decreasing effective channel capability.

In the following, the authors propose the adoption of a recently presented [5] substrate integrated transmission line, namely the Coaxial Substrate Integrated Waveguide (C-SIW) and compare it to the substrate integrated waveguide as an alternative for high-speed interconnects. Simulation results demonstrates that C-SIW can be conveniently used to implement very high-speed, undistorted data transmission, avoiding costly and time consuming additional circuitry with respect to traditional SIWs.

In the paper some technological and device aspects of the two IW structures are described in section II; section III concentrates on frequency domain simulations of both structures; in section IV results for time domain analysis are presented, together with a quantitative comparison among the

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two waveguides; finally, in section V some conclusions are presented.

2. SUBSTRATE INTEGRATED WAVEGUIDES

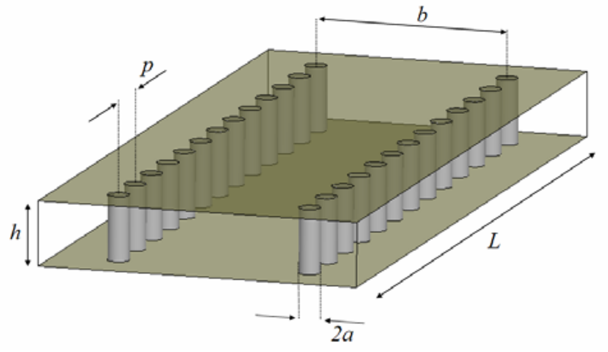
Substrate Integrated Waveguiding structures have been recently introduced to replace conventional metallic waveguides in the low millimeter wave frequency range (30-50 GHz) [6-7]. The simplest structure that can be devised is built realizing, on a conventional board of laminate, an array of metalized vias to form a waveguiding channel, as depicted in fig.1a. In this particular waveguide, only modes which are transverse electric to the axis of the channel (TE_{n0}) can be excited [6-7]. Recently, a number of SIW-based high frequency devices, have been presented. To mention a few, filters [7-8], antennas [9], and mixers [10] have been realized. In [11] the realization of a complete SIW based receiver has been reported. The propagation characteristics of SIWs have been investigated in many papers [12-15] and are here briefly summarized:

- The propagation constant as a function of the frequency of operation is analogous to that of an equivalent metallic conventional waveguide with dimensions related to the geometry of SIW. The dispersion characteristics of the guide are equal to that of the equivalent metallic waveguide. In SIW cut off frequencies, group delay and pulse deformation are observed as in metallic waveguides;
- Attenuation depends both on dielectric and ohmic losses, similar to what occurs for metallic waveguides. A further contribution comes from the power lost because of the leakage due to the imperfect shielding of the array of vias. However, if the inter-element spacing is small enough the power leaking away is negligible;

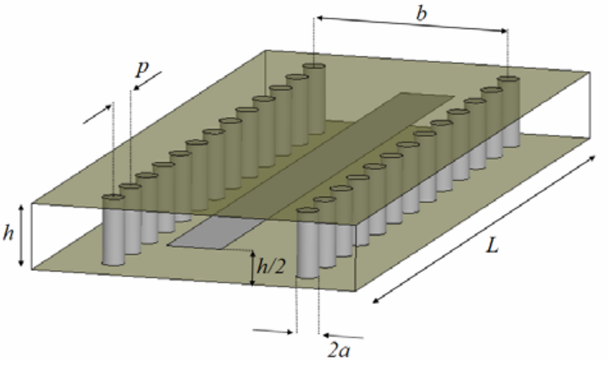
SIW have already been proposed as interconnects to convey digital signals between distant modules of a digital device. In this application the existence of a cut-off frequency requires that signals have to be raised to frequencies beyond cut-off. Furthermore, it is recommendable that signals should be modulated to a frequency of operation well beyond cut-off, anyway providing for them to remain far enough from the next-mode (higher) cut-off frequency. In this way the waveguide is operated in a frequency range where the propagation constant is a linear function of the frequency to avoid the effects of frequency dispersion.

However, this solution results in a complicated and costly auxiliary circuitry, as already stated in the introduction. As a further problem, because the cut-off frequency increases as the width of the SIW decreases, a lower limit on the SIW width has to be imposed to avoid cut-off frequency being too high. A structure alternative to SIW which does not show the problems previously listed above, but that can be realized with the same SIW technology, is the Coaxial-SIW (C-SIW). The structure is shown in fig.1b. It can be realized with two boards of laminate with a metallic strip between them and two arrays of via holes realized through the boards to connect the two ground planes. As is evident, the structure is a printed version of a rectangular coaxial transmission line. With respect to SIW, this novel structure presents the following differences:

- C-SIW has a multi-connected geometry and supports TEM waves with no cut-off frequency. A linear relation between propagation constant and frequency is expected at all frequencies avoiding problems due to frequency dispersion. Consequently, digital signals can be directly injected on the transmission line without requiring them to be modulated to a higher frequency, resulting in a simpler and cheaper circuitry and a consequent energy saving;
- dielectric and conductor losses are expected to be higher than SIW, as in the case of the conventional metallic counterparts. However, it will be shown that, as C-SIW can be operated at lower frequencies, the actual losses prove to be lower than those of SIW for a given data rate;
- the realization process is slightly more complicated than SIW because two layers are needed for the realisation of the waveguide. However, as C-SIW has no cut-off, its width is virtually limited only by the technology adopted to realize the structure.



a)



b)

Figure 1. Diagram of the two waveguide-based interconnect analysed: a) Substrate integrated waveguide b) Coaxial Substrate integrated waveguide.

In the following sections, the propagation characteristics in both frequency and time domain of the structures (SIW, C-SIW) will be analyzed and compared.

3. FREQUENCY DOMAIN ANALYSIS

The analysis in the frequency domain of SIW structures has been carried out in the literature by means of several techniques. The boundary integral-resonant expansion method (BI-RME), the finite difference in frequency domain (FDFD), the method of lines and the EFIE method of moments [12-14], all combined with the Floquet mode expansion, have been used to determine the propagation characteristics of the post walled waveguide.

Approximate models [15] have also proved to be quite effective to provide the propagation characteristics of integrated waveguides.

In this work, the frequency domain analysis of waveguide is performed with the aid of the commercial FEM package HFSS. In particular the propagation and attenuation constant of both SIW and C-SIW are investigated and compared. A SIW structure realized on a Rogers RT/DUROID 5880 substrate with thickness h=0.76mm, dielectric constant ε_r =2.2 was considered. The geometrical parameters of the guide are: via hole radius a = 0.24mm, pitch p = 0.68mm, waveguide width between center of the vias b = 4.1mm. Simulations were considered between 0 and 100 GHz. The waveguide length is 40mm. Fig. 2 shows the propagation constant as a function of the frequency, showing SIW behaves like a metallic waveguide. The cut-off frequency is located at 27 GHz.

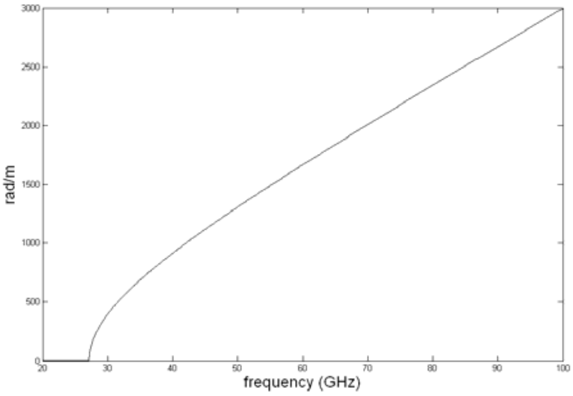


Figure 2. Propagation constant of analysed SIW as a function of the frequency.

On these bases, a frequency of 40 GHz was chosen for the carrier. To avoid signal distortion, the waveguide has to be operated at frequencies for which the propagation constant is a linear function of frequency, i.e. comprised between first and second cut-off frequencies, located at 27 and 54 GHz, respectively. The attenuation constant as a function of the frequency is reported in fig.3.

The plot was obtained considering copper as a conductor with σ= 58 10^6 S/m and a tanδ= 0.0009 for the dielectric, also included are the losses owing to power leaked through the vias which is negligible in the case considered in this paper.

In fig.4 the propagation constant as a function of signal frequency in the case of a C-SIW is reported.

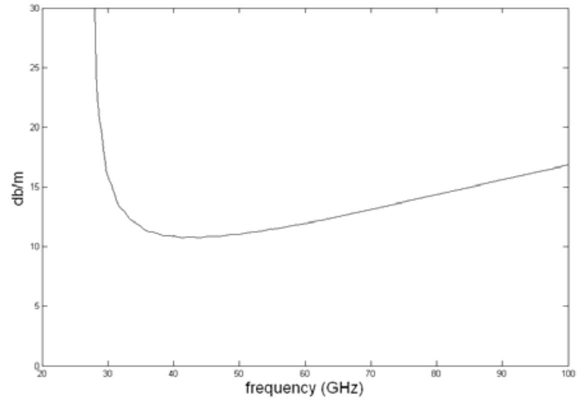


Figure 3. Attenuation constant of analysed SIW as a function of the frequency.

Simulations were carried for a coaxial waveguide with the same geometrical dimension of SIW counterpart.

The thickness and the width of the metal (copper) strip are 10μm and 0.631mm, respectively, so as to obtain a characteristic impedance of 50Ω.

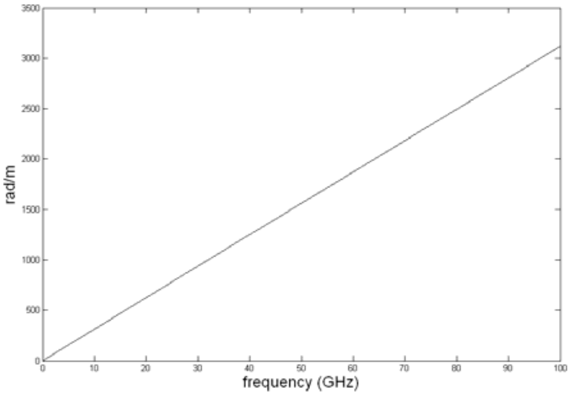


Figure 4. Propagation constant of C-SIW as a function of the frequency.

The coaxial structure supports a TEM wave and, as it could be expected, no cut-off frequencies are present. Furthermore, the propagation constant is a linear function of frequency in the entire range considered. For these reasons a digital signal can propagate along a C-SIW without requiring to be carried to higher frequency.

This latter characteristic gives advantages in terms of simplicity and costs of drivers and receivers, but also in terms of power losses. In fact, observing plots of the attenuation constant for the two structures presented in fig. 3 and fig. 5 it can be seen that at lower frequency the attenuation constant of a C-SIW is lower than the one presented by an SIW.

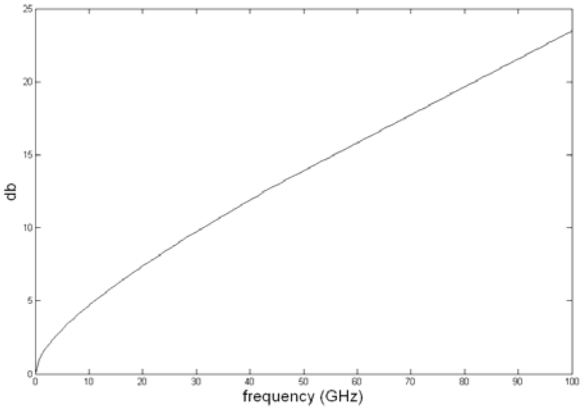


Figure 5. C-SIW attenuation constant as a function of the frequency.

As an example, for a digital signalling with an equivalent frequency of 1.65 GHz, also used for the time domain simulations presented in the next sections, the C-SIW shows an attenuation of about 1dB/m, whereas the same signal, modulated at 40 GHz to overcome bandpass behaviour of the guide, experiences an attenuation around 11dB/m for the SIW, as shown in Fig. 6.

Moreover, C-SIW cross-section width can be reduced by decreasing the distance between the vias, so as to save PCB or IC routing area, without significantly affecting propagation characteristics.

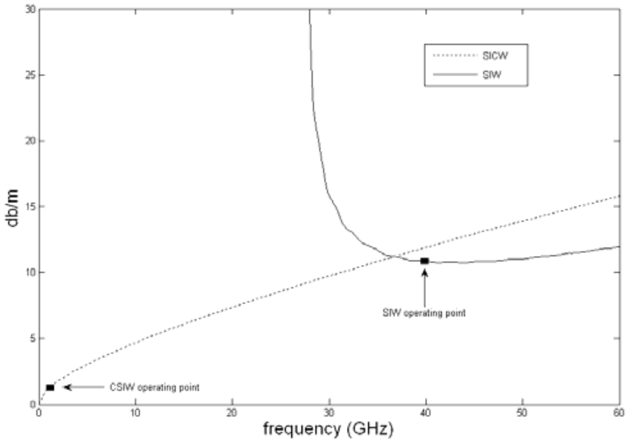


Figure 6. Operation Frequency comparison of the two structures.

To highlight this important issue, fig. 7 compares attenuation constants of the original C-SIW and a more compact version with a width between the center of the vias *b* = 1.48mm.

Plots regarding propagation constants have not been reported since no appreciable difference exists between the two cases.

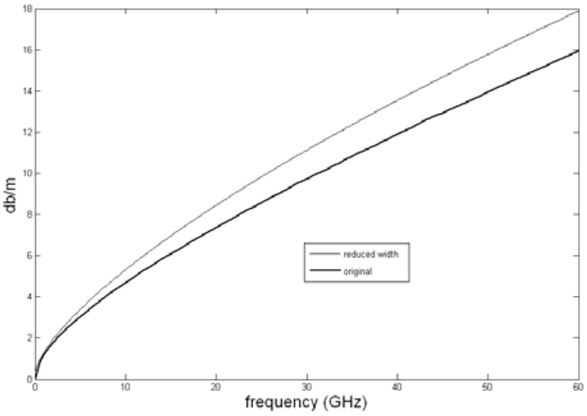


Figure 7. Attenuation constant comparison between the original and a reduced-width C-SIW.

4. TIME DOMAIN BEHAVIOUR

To compare the timing performances of the two structures a time domain analysis was performed using an FDTD-based code. A bit rate of 1.66Gb/s and rise/fall times of 50ps were used in system simulations. Transmitted data being composed of a sequence of digital pulses, they are characterised by a lowpass spectrum while the transmission channel, in the case of SIW, has a bandpass characteristic. Therefore, a modulation/transmission system, such as the one in [4] and reported for convenience in fig. 8, should be used. In the scheme, the modulation and demodulation processes are achieved by using mixers implemented in the driver and receiver stages, respectively. The baseband signal is initially modulated by a mixer. The frequency of modulation is chosen around the center frequency between the cut-off frequencies of the TE_{10} and TE modes, using a local oscillator (LO) with a frequency of 40 GHz. The signal obtained by the modulation stage is launched into the waveguide.

Figure 8. The baseband transmission system required for SIW operation.

The signal at the far end is then down-converted by a second mixer with the same LO frequency as the mixer user in the driver stage. In the case of C-SIW, the waveguide can be directly fed with the test baseband signal, thanks to the absence of cut-off frequencies. Four patterns representing 011, 001, 100 and 110 transitions, respectively, were propagated in both structures.

The responses to the four patterns are superimposed to create the eye diagrams shown in fig.9 and 10.

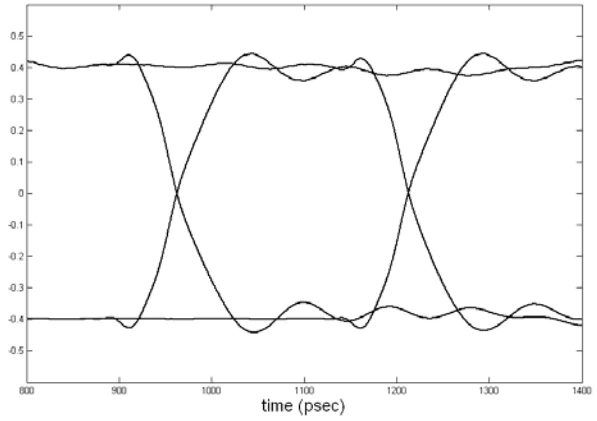


Figure 9. Eye diagram for a (011, 001, 100, 110) data pattern for SIW.

As shown, the conventional SIW waveguide is characterised by the presence of persistent ringings and strong degradation in the transition time of signals, this latter rising from 50ps to about twice, owing to its dispersive behaviour.

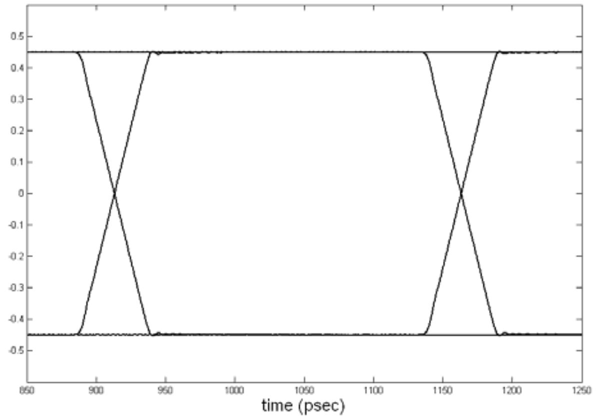


Figure 10. Eye opening diagrams for a (011, 001, 100, 110) data pattern for C-SIW.

The C-SIW simulation shows an undistorted eye diagram, demonstrating an accumulated dispersion near to zero. Ringing is negligible and rise and fall time of signals are unchanged with respect to the ones of the original signal, thus demonstrating more promising performances for simpler and more effective digital interconnects networks.

5. CONCLUSIONS

In this paper an analysis of the propagation characteristics of integrated waveguides as interconnects is presented.

The study compares the performances of "conventional" substrate integrated waveguides with the newly introduced coaxial substrate integrated waveguide. Dispersion characteristics and attenuation were studied, showing superior performances of the C-SIW. Moreover, owing to the absence of cut-off frequencies, the C-SIW structure results to be more attractive for digital signalling, owing to the absence of additional circuitry for signal modulation, thus avoiding costly and power-hungry driver and receiving devices.

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