Dispersion and Field Control in a Metasurface-Implanted Waveguide

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***Abstract*—Dispersion and cutoff frequency are essential parameters for microwave waveguides and their versatile applications in communication and sensing. In this work, we propose the concept of substrate-integrated impedance surface (SIIS) that enables arbitrary control of dispersion in closed-shape waveguides and demonstrate that a substrate-integrated waveguide (SIW) loaded with a capacitive SIIS (e.g., an array of blind vias) does not have only a reduced cutoff frequency, but also exhibits effects of slow-wave propagation and field localization. The proposed SIIS technique may have broad relevance beyond miniaturization of waveguide components, as it may also open exciting prospects for ultrasensitive microwave sensing and enhancement of nonlinear properties in active waveguides.**

I. INTRODUCTION

Waveguides have been widely used in microwave circuits and integrated systems, due to their merits of high power-handling capability and low transmission loss [1]. They have been be extensively used not only to transmit electromagnetic waves, but also to implement various radio-frequency and microwave components, such as antennas, filters, resonators, couplers, and phase shifters. In the past decade, substrate-integrated waveguides (SIW) have found applications in design of microwave and millimeter-wave circuits [2], since they are planar and low-profile, and offer benefits of a rectangular waveguide, such as high power-carrying capacity and high quality factor. Unlike conventional bulky metallic waveguides, SIWs significantly ease the integration with planar circuits and have good compatibility with the high-yield print circuit board (PCB) and the complimentary metal-oxide-semiconductor (CMOS) manufacturing processes.

In this work, we propose the concept of substrate-integrated impedance surface (SIIS) that can tailor the cutoff frequency, dispersion, and field distributions of an SIW or any closed-shape waveguide, as illustrated in Fig. 1. An SIIS can, for instance, be formed by a one-dimensional (1-D) blind-via array, which, together with its mirror image inside the waveguide, effectively make an impedance surface with a homogenized surface impedance. This concept is, in some sense, similar to a planar metasurface or frequency selective surface embedded in a waveguide medium.

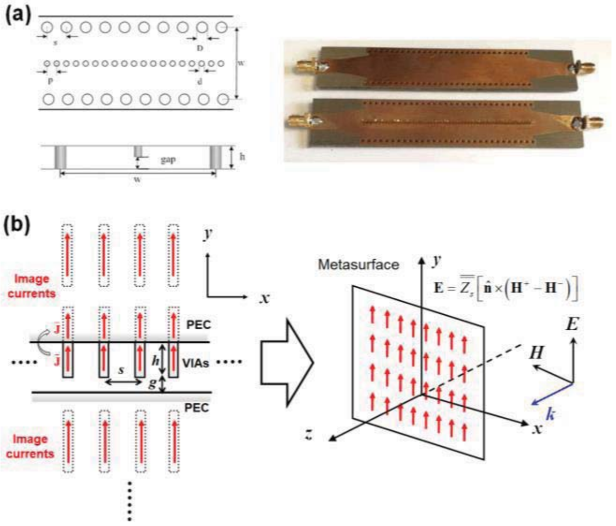

Fig. 1. (a) Schematics and photograph of a miniaturize metasurface-implanted substrate-integrated waveguide. (b) Conceptual illustration of substrate-integrated impedance surface realized with interconnect networks in the on-board or on-chip microwave circuit.

II. THEORY AND EXPERIMENTS

At microwave frequencies, a single blind via with height h (through-hole via), radius a, and gap g, located in between two parallel metal plates of an SIW can be equivalent to one column of discrete (or continuous) wire array, as shown in Fig. 1. As a result, a physical wire and its imaged counterpart mirrored by the metal layer could form a shunt impedance surface implanted in the SIW. In this case, the tangential magnetic fields on the two sides of the SIIS are related to the tangential electric fields by the surface impedance Z_s as $E_{x+}=E_{x-}=Z_s\left[\hat{z}\times\left(H_{y+}-H_{y-}\right)\right]$. For the dominant TE_{10} mode, the dispersion equation of an SIIS-implanted SIW can be derived as:

$$\frac{-i\omega\mu_0}{2\sqrt{k^2-\beta^2}}\tan\left[\sqrt{k^2-\beta^2}\,\frac{w}{2}\right]+Z_s(\omega)=0 \qquad (1)$$

where $k=\omega\sqrt{\varepsilon\mu_0}$ is the wavenumber, ω is the angular frequency, w is the width of the SIW, and ε is the permittivity of the dielectric medium inside the SIW. In principle, there is no limit on the cutoff frequency of an SIW, provided that the required Z_s can be achieved at the working frequency. Considering the full coupling among the whole array of interacting electric dipoles (subwavelength cut-wires [Fig. 1b]), The average sheet impedance of the SIIS, as the ratio of the local electric field to the surface current density J_s, can be expressed as:

$$Z_s=\frac{E_{ext}}{J_s}-\frac{\eta}{2}=-\frac{d_x d_y}{i\omega}\left(\alpha_{xx}^{-1}-C_{int}\right)-\frac{\eta}{2} \qquad (2)$$

where α_{xx} is the first diagonal element of the electric polarizability tensor $\overline{\overline{\alpha}}$, d_x and d_y are periods of dipoles, and C_{int} is the interaction constant [3]. For a single thin and short conducting wire, the real and imaginary parts of the polarizability can be explicitly written as [3]:

$$\mathrm{Re}\left(\alpha_{xx}\right)=\frac{4\varepsilon\pi h^3}{3\left[\ln\left(2h/a\right)-1\right]};\ \mathrm{Im}\left[\alpha_{xx}^{-1}\right]=-\frac{k^3}{6\pi\varepsilon}. \qquad (3)$$

In the quasi-static limit, the real part of the interaction constant can be approximated as [4]:

$$\mathrm{Re}\left(C_{int}\right)\approx\frac{c}{\varepsilon\left(d_x d_y\right)^{3/2}};\ \mathrm{Im}\left[C_{int}\right]\approx-\frac{k^3}{6\pi\varepsilon}+\frac{\eta\omega}{2d_x d_y}, \qquad (4)$$

where c is an empirical fitting parameter. From Eqs. (2)-(4), the surface impedance of the SIIS can be expressed as:

$$Z_s=-\frac{1}{i\omega C_s} \quad \text{and} \quad C_s=\frac{\varepsilon/d_x d_y}{\dfrac{3\left[\ln\left(2h/a\right)-1\right]}{4\pi h^3}-c/\left(d_x d_y\right)^{3/2}}. \qquad (5)$$

Fig. 1(a) shows the photographs of the fabricated SIIS-loaded SIW; here, the length and width of the SIW are 90 mm and 20 mm, respectively. Fig. 2(a) presents the simulated (dashed) and measured (solid) transmission coefficients (S_{21}) of the standard and SIIS-loaded SIWs in Fig. 1(a). In all cases, the simulation and measurement results agree quite well. A good insertion loss (< -3dB) is obtained for the standard and the SIIS-loaded SIWs. From Fig. 2(a), it is clearly evident that by loading the capacitive SIIS, the cutoff frequency can be downshifted from 5 GHz (standard SIW) to 4.25 GHz (SIIS-loaded SIW with g = 1.5 mm) and 3.75 GHz (SIIS-loaded SIW with g = 0.9 mm). The cutoff frequency decreases with reducing the gap size of the blind vias, due to the increased equivalent surface capacitance. As a result, SIIS could provide an effective means for miniaturization of waveguides. Fig. 2(b) presents the simulated (dashed) and measured (solid) real part of propagation constant for the waveguides in Fig. 2(a). Since the reactive SIIS provides an extra phase shift in the transverse direction, the waveguide dimension can be squeezed, accompanied with the effect of local field concentration. Fig. 2(c) compares the simulated distributions of field intensity inside the standard SIW (top) and the SIIS-loaded SIW (bottom), showing that the field intensity can be significantly enhanced by the implanted metasurface. An SIIS could play a similar role as a bulk metamaterial (which are usually highly-dispersive and lossy) in tailoring the waveguide properties, with reduced fabrication complexity and cost.

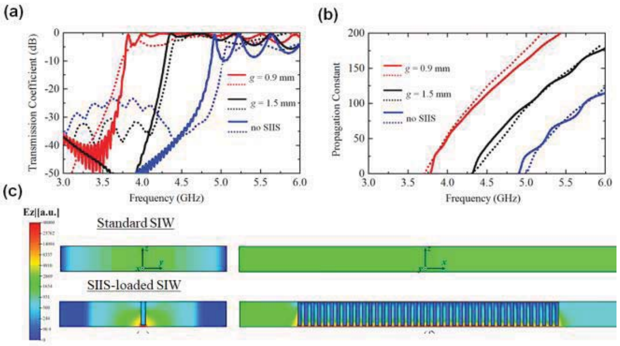

Fig. 2. (a) Reflection coefficient, (b) dispersion diagram, and (c) distributions of electric field intensity for the standard SIW and the SIIS-loaded SIW; here, solid and dashed lines represent experimental and simulations results, respectively.

III. CONCLUSIONS

We have discussed the control of cutoff frequency and dispersion of substrate-integrated waveguides by loading a substrate-integrated impedance surface constituted by interconnect networks. Different from the those metamaterial-based miniaturized waveguides, the proposed SIIS can be seen as a shunt, non-resonant surface impedance, enabling eased implementation complexity, low propagation loss, and high power-carrying capacity. This SIIS or implanted metasurface opens the possibility of engineering the propagation properties of various waveguide components. The giant field enhancement effect around an SIIS also opens up new possibilities for microwave sensors and nonlinear devices.

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