Wearable Spoof Surface Plasmon Polariton Transmission Line

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Abstract. In this work, we present a study of Spoof Surface Plasmon Polariton (SSPP) supported by a meandered Transmission Line (TL) dedicated to wireless body sensor network applications. First, dispersion curves evidence the existence of a surface wave propagation, called odd mode according to the symmetry of the magnetic field. This mode can be wirelessly excited with of a dipole antenna parallel-positioned above the meandered transmission line. Experimental part is validated with a SSPP TL fabricated on a Kapton substrate and compared with a wearable SSPP TL produced by embroidering a metallic yarn on a textile substrate. Second, transmission measurements for both SSPP TLs are also presented and compared. The difference of performances achieved between involved technologies is explained by the conductivity value of the metallic yarn. Finally, the use of embroidered SSPP TL shows an improvement of the transmission compared with the transmission in free space. This study is investigated in simulation and experiments by determining the dispersion curves and the transmission for two SSPP TLs.

Keywords: Spoof Surface Plasmon Polariton (SSPP), Smart textile, Wireless Body Area Network (WBAN).

1 Introduction

When operating at infrared and visible wavelengths, a surface wave can naturally propagate at the interface between a dielectric and a conductor with an evanescent electromagnetic field perpendicular to the interface [1]. This type of propagation is known as Surface Plasmon Polariton (SPP). Furthermore, at the same frequency, SPP is characterized by a dispersion curve with a value of the wave vector greater than in free space. It results a higher confinement of the electromagnetic fields at the interface, a slow wave propagation and a cutoff frequency emerges when the group velocity becomes zero. In microwave, recent studies have shown the possibility to propagate a surface wave by using the concept of metamaterials. Then it is named Spoof Surface Plasmon

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Polariton (SSPP) [2]. Different structures have been proposed to generate SSPP such as a one-dimensional array of grooves [3] [4], a two-dimensional array of square holes [2], metasurfaces of square patches [5] and mushroom structures [6] [7]. Generally, a surface wave is introduced on the metasurface by adding a metallic periodicity with a period lower than the wavelength (sub-wavelength condition). Otherwise, it was proven experimentally that the surface wave property is insensitive to the lateral width of one-dimensional array of grooves [3]. And there is only a downward shift of the dispersion curve when reducing the lateral thickness of a metallic corrugation down to subwavelength scale [8]. In addition, SSPP TLs can be wirelessly excited by near-field coupling using antennas [9] [10].

At last, Wireless Body Sensor Network (WBSN) has interested several applications on healthcare, telemedicine and sport. WBSN consists of several sensors placed all over the body with a worn gateway as a Smartphone, allowing to collect data from a Body Area Network (BAN) and re-transmit them to a wide area network. Hence, the introduction of a SSPP TL onto a textile as a waveguide to connect and to improve the transmission between sensors placed on the body is currently considered as a solution [11] [12]. However, a SSPP TL presented in a recent work was carried out by laser-cutting a conductive textile, and then glued it onto a dielectric textile substrate. This technique may introduce disadvantages such as a short service life due to a low resistance against washing.

In this paper, the embroidery technique is proposed to produce a meandered SSPP TL owing to the ease of fabrication. Nevertheless, structuring by metallic yarns can yield some difficulties in terms of homogeneity and low conductivity of the yarns. For this reason, the performance of an embroidered SSPP TL is evaluated and compared with an SSPP TL produced by traditional Printed Circuit Board (PCB) technology. The meandered TL proposed in this study is considered as a hollowed symmetric comb-shaped structure commonly used for supporting a SSPP [8]. Consequently, a reduction of the metallic part of the TL allows to reach both high flexibility and low cost for embroidery production.

2 Results and Discussion

2.1 Dispersion curve of the odd mode

Dispersion curve was simulated by means of the eigenmode solver of Ansys HFSS software. Fig. 1 shows the unit cell of the meandered TL with the geometric parameters and the simulation conditions used to calculate the dispersion curve. As illustrated in Fig. 1(a) and according to the magnetic field which is mainly oriented in the *z*-direction, a periodic condition (master-slave) was put in the y-z plane, and a Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) was used in the *x-y* and *y-z* plane, respectively.

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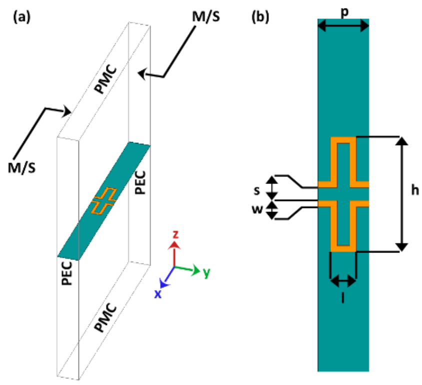

Fig. 1. Unit cell of the meandered TL used to calculate the dispersion curve with (a) boundary conditions and (b) geometric sizes with p=8 mm, h=18 mm, s=2 mm, w=1 mm and l=4 mm.

The dispersion curve plotted in Fig. 2 is attributed to an odd mode as shown by the magnetic field mapped in the inset of Fig. 2. This propagation mode corresponds to a symmetric magnetic field around the two meandered strips produced when the current in each meandered strip circulates in the same direction. In addition, its wave vector k is higher than k_0 in free space propagation shown by the light line in Fig. 2. Therefore, a high trapping of the wave around the meandered TL is expected. The simulated dispersion curve presented in Fig. 2 was done by using a 50 µm-thick Kapton substrate with a complex permittivity ε_r=3.2(1 -i 0.03). However, as the Kapton and textile substrates used in this study are very thin, the simulated dispersion curve is similar for both substrates and it can be directly compared with experimental results measured for samples fabricated by PCB and textile technologies.

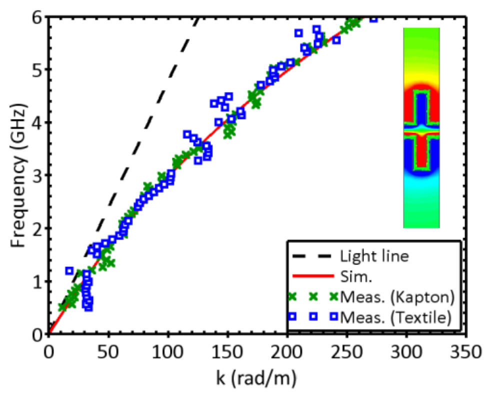

Fig. 2. Simulation (Sim.) and measurements (Meas.) of the dispersion curve of the odd mode supported by the meandered TL. In inset, z-component of the magnetic field (H_z).

The odd mode previously studied by means of the dispersion curve can be wirelessly excited by means of a dipole antenna parallel-positioned above the meandered TL. The SSPP odd mode can be excited by magnetic coupling of the dipole antenna with the meandered TL. As shown in Fig. 3(b), the symmetry of the magnetic field is similar to the symmetry obtained by the dispersion curve calculation. As a consequence, the horizontal polarization of the dipole antenna positioned above and parallel to the TL is able to generate the SSPP odd mode.

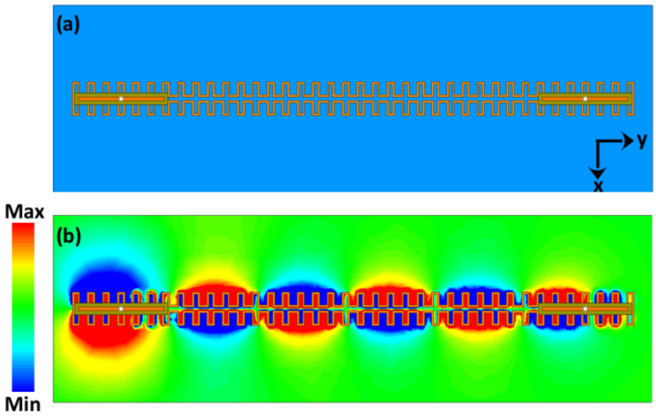

Fig. 3. (a) Simulated meandered TL and the wirelessly excited odd mode propagation by means of dipole antennas in horizontal polarization. (b) *z*-component of the magnetic field (H_z) plotted in the *x*-*y* plane at $f = 2.15$ GHz.

The measured dispersion curve of the odd mode was done by using a relevant method commonly used to determinate the complex permittivity by means of connected TLs [13] [14]. This method consists of calculating the eigenvalues of a computed matrix involving the S parameters measured for two identical TLs of different lengths. In the present study, the de-embedding method has been applied for only one TL wirelessly excited by the dipole antennas. The Scattering parameters were measured for two distances between antennas by only moving the antennas at two positions above the TL. This method is extensively described in [10]. The experimental dispersion curves are shown in Fig. 2 for both SSPP TL fabricated on flexible PCB substrate (Kapton) and on a textile substrate by embroidery technique. The experimental results represent a satisfactory agreement with the simulation ones. Also in terms of the curve dispersion, the performances of the embroidered SSPP TL and of the SSPP TL fabricated by traditional PCB technology are the same.

2.2 Wave transmission supported by the odd mode

An embroidered TL of 300 mm-length was manufactured by using the computer-aided embroidery machine JF-0215-495 from ZSK Company and a silver-based conductive yarn Shieldex® Twisted Yarns 117/17 dtex 2-Ply from Statex Company [15]. The embroidery was done by using a conductive yarn of diameter around 0.2 mm in upper threading and a polyester dielectric yarn in lower threading (bobbin). They were together embroidered onto a 0.28 mm-thick substrate of cotton which is characterized by a measured permittivity ε_r=1.8. For the sake of minimizing the conductive losses in the meandered TL, the structuring of embroidery was oriented in the direction of the current flow through the TL. The performance of the embroidered TL is also compared with the results measured for a TL fabricated on Kapton by PCB technology. As shown in Fig. 4, the PCB and embroidered SSPP TLs were characterized by using two dipole antennas connected to a VNA by coaxial cables. The antennas were manufactured on a FR4 substrate of thickness 1.6 mm. The geometric sizes are shown in the inset of Fig. 4. The back-side of the antenna substrate were directly placed on the meandered TL by preventing any air gap between them. Before starting the characterization, the VNA was calibrated using a SOLT (Short-Open-Load-Thru) calibration. Moreover, a commercial microwave absorber Eccosorb AN-75 was used behind the antennas in order to avoid unwanted interferences with the metallic holders.

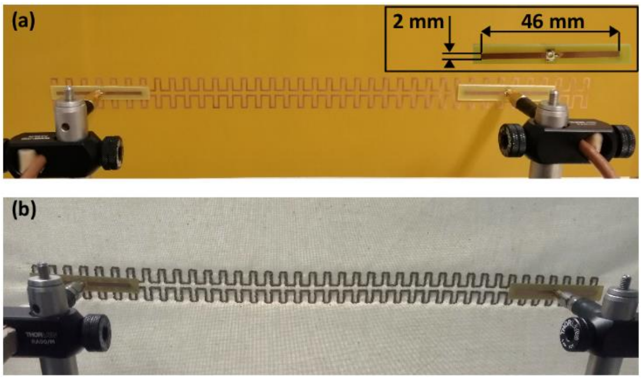

Fig. 4. Experimental setup for determining the odd mode transmission of the meandered TL fabricated by (a) PCB (Kapton) and (b) embroidery technique, respectively. In inset, the geometric sizes of the dipole antenna.

The transmission measured between antennas is shown in Fig. 5 for PCB and embroidered TLs and it is compared with the simulation results. The simulated transmission for the embroidered TL was calculated by considering a conductivity $\sigma = 1.5\ 10^4$ S/m for the metallic strips and a good agreement was obtained with the measured transmission. On the other hand, the transmission measured for the TL on Kapton substrate (PCB) is compared with the simulated transmission when considering a conductivity of copper for the metallic strips. Almost the same transmission trend was obtained for both TLs with a slight difference between them observed at the maximum value of the transmission. The maximum measured transmission for PCB and embroidered TL is around -6 dB and -10 dB respectively. The difference of 4 dB between the two SSPP TLs can be related to the conductivity of the metallic yarn which is three orders of magnitude lower than the copper conductivity. Moreover, the measured transmission for the embroidered TL is compared with the measured transmission in free space and a transmission improvement is achieved. The transmission between antennas is improved around 11 dB and 28 dB by means of the embroidered TL comparing with the transmission measured in free space between vertical-oriented (V-Antennas) and horizontal-oriented (H-Antennas) antennas, respectively. As shown in Fig. 5(b), the maximum value of the transmission is observed at 2.7 GHz when the vertical-oriented parallel antennas radiate in free space. When using the SSPP TL, the maximum value of the transmission is shifted down to 1.8 GHz. This frequency shift is produced because of near field coupling of the antenna with the SSPP TL.

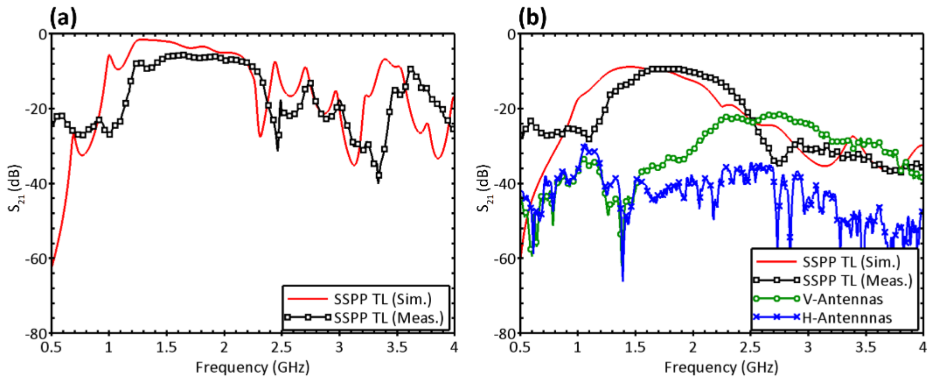

Fig. 5. Simulated (Sim.) and measured (Meas.) transmission for the odd mode supported by the (a) PCB and (b) embroidered SSPP TL. (b) Comparison with the transmission measured in free space between vertical-oriented (V-Antennas) and horizontal-oriented (H-Antennas) antennas.

3 Conclusion

As a conclusion, the SSPP odd mode have been wirelessly excited by means of horizontal polarization dipole antennas parallel to the TL. The measured dispersion curve of an embroidered SSPP TL showed a good agreement with the dispersion curve of a PCB SSPP TL. The maximum transmission of the embroidered and the PCB TLs showed around 4 dB of difference between them. This difference has been related to a lower value of the conductivity of the metallic yarns compared with copper. Moreover, the embroidered TL allowed to improve the transmission of around 11 dB and 28 dB by comparison with the transmission in free space when the antennas were vertically- and horizontally-oriented, respectively. Finally, the embroidered TL presented in this work can be considered as a waveguide dedicated to wireless body sensor network applications with performance enhancement.

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