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ORIGINAL RESEARCH

Embroidered Spoof Surface Plasmon Polariton Transmission Line for Wireless Body Sensor Network

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Abstract

A wearable Spoof Surface Plasmon Polariton Transmission Line (SSPP TL) operating at 2.45 GHz designed for embroidery production and on-body communication is proposed. The SSPP TL supports both even and odd modes launched by near field coupling with a dipole antenna perpendicular and parallel to the TL, respectively. First, the experimental dispersion curves and transmission for the even and odd modes are favourably compared to simulations. Then, experimental transmission for each mode is compared with the Line-Of-Sight (LOS) transmission between two parallel-oriented antennas. At 2.45 GHz, a transmission enhancement of 16 dB is measured for the even mode and it reaches up to 37 dB for the odd mode. A transmission enhancement of 30 dB is also measured at 2.45 GHz between two antennas with orthogonal orientations. Performances of the SSPP TL for Wireless Body Sensor Network are evaluated. Transmission is sustained for the SSPP TL under curvature and right angle bending. Transmission measured when both an arm and a copper plate obstacle between antennas were surrounded by the curved SSPP TL is compared with the obstructed LOS transmission. Measurements show a transmission enhancement up to 22 and 25 dB for the even and odd modes, respectively.

KEYWORDS

electromagnetic metamaterials, surface plasmons, transmission lines, waveguides, wireless LAN

1 | INTRODUCTION

Since the early 2000s, Wireless Body Sensor Networks (WBSNs) has met the increasing consumer demand for technologies dedicated to healthcare, telemedicine, and safety but also for wellness (fitness activities and sport training performance) and entertainment applications (movement recognition in games as an example). A WBSN consists of sensors implanted on or in close proximity to the human body measuring physiological, vital signs, or movement data and transmitting them to a coordinator unit. Then, the measured data can be collected, processed and monitored by a mobile phone or by means of an external cloud [1]. In a WBSN, wireless communications between sensors and the coordinator unit can suffer from human body proximity, which can deteriorate the antenna performance with frequency shift,

impedance mismatch and radiation pattern distortion [2–5]. Moreover, if data are transmitted in free space through the body, the link budget is drastically reduced due to high attenuation by human tissues [6–9].

For improving the propagation characteristics of on-body communications, Non-Line-Of-Sight (NLOS) links were involved by integrating supplementary waveguides on clothing [10–13]. By using a strip line or a segmented coplanar waveguide, a 20 dB improvement of the transmission was achieved compared with transmission between two patch antennas in free space. Moreover, such wearable waveguides can be wirelessly connected by coupling to antennas avoiding the irrelevant and problematic need of connectors in smart textiles [10, 11, 14]. A wearable and wireless network based on Spoof Surface Plasmon Polariton Transmission Line (SSPP TL) was also proposed with a 30 dB enhancement of the transmission

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efficiency together with an electromagnetic field localisation within 10 cm of the body [12]. As a generality, an SSPP TL supports slow wave modes with a spatial confinement of the electromagnetic field decaying away perpendicular to the TL. Consecutively, SSPP TL is a promising candidate for WBSN technologies because the spatial confinement limits interaction of the guided wave with the human body and a higher data security can be expected with a localised transmission nearby a personal smart garment. At last, SSPP-based WBSN might benefit from the numerous development dedicated to system miniaturisation, thanks to slow wave propagation [15–18].

The SSPP TL used in the study by Tian et al. [12] was patterned by laser-cutting a conductive textile and then by stacking conductive and dielectric textile materials glued together with fabric adhesive. This technology looks like a flexible Printed Circuit Board (PCB) with two textiles as substrate and conductive patterns, and other textile technologies might be more convenient for end users. Although all the textile technologies as knitting, weaving, and embroidery were already proposed for integrating antennas or filtering functions in smart textiles [19–21], embroidery has become the most popular because of the ease of fabrication [19, 22–24]. However, there are some drawbacks compared to more traditional technology such as flexible PCB, which have to be taken into account in the design stage. The first ones are relatively high cost conductive yarns and cause stiffening of the embroidered fabric with a risk to produce uncomfortable technology for end users.

In this article, performances of a wearable SSPP TL designed for WBSN application operating at 2.45 GHz and realistic embroidery production are evaluated. The SSPP TL is able to support two modes, each of them wirelessly excited by means of a perpendicular or parallel-oriented dipole antenna with the TL. Experiments show a transmission enhancement by the SSPP TL compared with free space together with polarisation insensitivity. Experimental transmission under right angle bending and in the presence of a human body is also analysed. Compared with the SSPP TL used in the study by Tian et al. [12], the proposed structure is able to support two modes and is less sensitive to the antenna orientation. Moreover, it should be more robust to successive washes, which can deteriorate the fabric adhesive used in the study by Tian et al. [12] and take off the conductive pattern. Finally, the proposed structure should be more easily accepted by some end users because embroidered clothes are already commonly known by people.

2 | SPOOF SURFACE PLASMON POLARITON MODES

Geometry and size of the SSPP TL are defined in Figure 1. The SSPP TL consists of two parallel 0.2-mm-thick meander-shaped strips on a thin substrate without a ground plane on the back side. It can be considered as a hollowed symmetric comb-shaped structure commonly used for guiding SSPP [17]. As the metallic part of the TL is reduced, both high flexibility and low cost are reached for embroidery production. A meandered TL

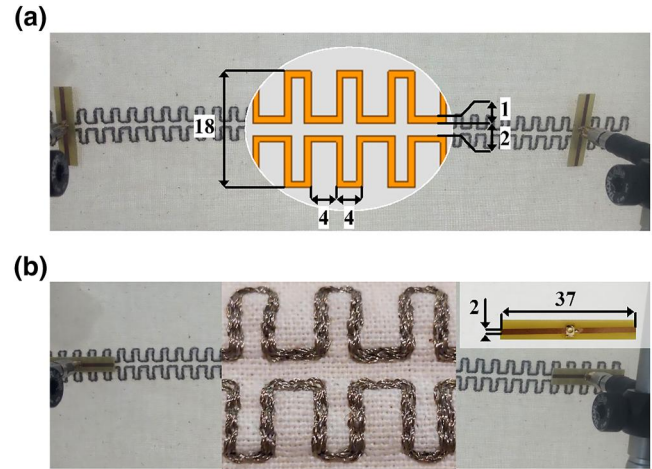


FIGURE 1 Geometry and size of the embroidered Spoof Surface Plasmon Polariton Transmission Line (SSPP TL; Units: mm). Experimental setup for (a) the even mode with vertically oriented dipole antennas and for (b) the odd mode with horizontally oriented antennas. In the inset, the size of the dipole antenna (Units: mm) and photograph of the manufactured SSPP TL

operating at 2.45 GHz was first designed with the commercial software HFSS by Ansys by considering strips as Perfect Electric Conductors (PEC) and a cotton fabric of permittivity $\epsilon_r = 1.8$ as a 0.28-mm-thick substrate. Permittivity and thickness of the cotton fabric were measured prior to design. The SSPP TL 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. Conductive yarn was used in upper threading (sewing thread) and a polyester dielectric yarn for lower threading (bobbin thread). They were together embroidered onto the cotton fabric. In order to reduce metallic loss, the embroidery stitch was selected in the direction of the current flow through the TL, that is, straight stitches following the meander-shaped strips [25]. The stitch length was 1 mm and the width of the strip (1 mm) was produced by successively embroidering five parallel yarns close together. The effective conductivity of the strips depends on the density of yarns. For low density, the effective conductivity decreases because the number of electric contacts between adjacent embroidered yarns decreases. For high density, the needle of the embroidery machine could crash into the previously embroidered yarn during successive embroidering, damage conductive yarn, and reduce effective conductivity as a consequence. Therefore, the density of yarns has to be selected in order to have enough electric contacts between adjacent yarns and to avoid any risk of damaging yarns.

In order to assess transmission by simulation and experiments, the guided wave was launched by means of a dipole antenna shown in the inset of Figure 1b and patterned on a 1.6-mm-thick FR4 substrate. A part of the experimental setup is illustrated in Figure 1. The antennas were put directly onto the embroidered SSPP TL with the back side of the substrate contacting the TL (if not otherwise specified).

Experimental results were measured by means of a Vector Network Analyser previously calibrated according to Short-Open-Load-Thru (SOLT) calibration. The distance between antennas for all measurements was approximately 25 cm. Finally, the Line-Of-Sight (LOS) transmission in free space between antennas were measured when the SSPP TL was removed for comparison. In order to characterise the propagation properties of the SSPP modes, the dispersion curves plotted in Figure 2 were first simulated by using the eigenmode solver of HFSS [26]. The SSPP TL supports two modes below a cut-off frequency higher than 6 GHz (not shown). Here, the mode parity was defined by mapping the magnetic field around the SSPP TL as shown in the inset of Figure 2 with the even (odd) mode corresponding to a symmetric (antisymmetric) field, as commonly considered for SSPP [26]. It is worth mentioning that the symmetric (antisymmetric) magnetic field is produced by currents flowing through the meander-shaped strips in opposite (same) directions. That means the considered parity definition is inverted in comparison with the even and odd modes of the coupled lines theory [27].

The experimental dispersion curves plotted in Figure 2 were assessed by means of a de-embedding method involving scattering parameters measured for two different distances between antennas either vertically- or horizontally oriented [26, 28]. As shown in Figure 2, experimental curves fit simulations indicating that the even and odd modes were correctly wirelessly generated by means of vertically- and horizontally oriented dipole antennas, respectively [26]. We can note that due to the thinness of the textile, the dispersion curves are not sensitive to the permittivity of the substrate. Especially, the same dispersion curves were achieved for an SSPP TL with the same sizes and geometry etched on a flexible substrate Kapton [26].

The transmission measured between two vertically- or horizontally oriented antennas with and without the SSPP TL is plotted in Figure 3 together with the simulated results. Experiments confirm the simulated transmission with a maximum value of -21 and -13 dB for the even and odd modes, respectively. For the sake of comparison, the simulated transmission plotted in Figure 3 was calculated by considering a conductivity $\sigma = 10^4$ S/m for the embroidered strips and not by PEC as for the dispersion curves. By considering strips as PEC, a higher transmission around -3 dB can be achieved because the conductive losses are suppressed. Also, we can mention that a higher transmission (-6 dB) for the odd mode was measured (not shown) for a copper meander-shaped SSPP TL on flexible substrate Kapton. Without SSPP TL, a transmission maximum is observed at 3.14 GHz between parallel vertically oriented antennas. This maximum corresponds to the impedance matching of the antenna radiating in free space. When coupled with the SSPP TL, the transmission maximum for the even mode is shifted down to around 2.2 GHz with a pass-band feature extending from 1.9 to 3.1 GHz. The frequency shift is consecutive to near field coupling of the antenna with the SSPP TL. A higher frequency shift is also observed for the odd SSPP mode with a maximum of transmission at 2 GHz and a 1.8–2.6-GHz bandwidth. The

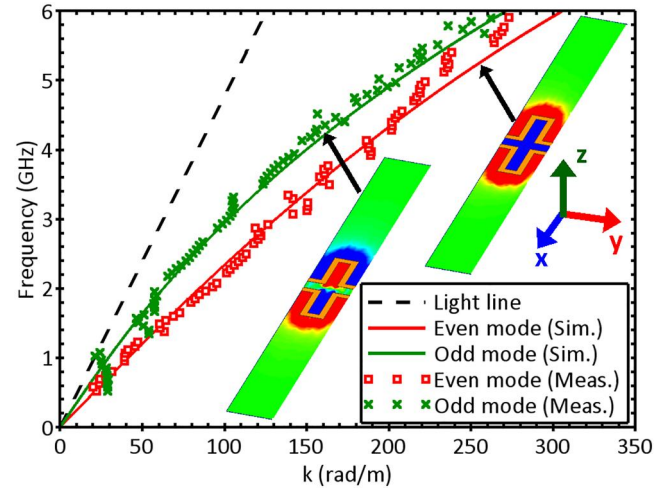


FIGURE 2 Simulated and experimental dispersion curves for the even and odd modes supported by the Spoof Surface Plasmon Polariton Transmission Line (SSPP TL). In the inset, z -component of the magnetic field simulated for the even and odd modes

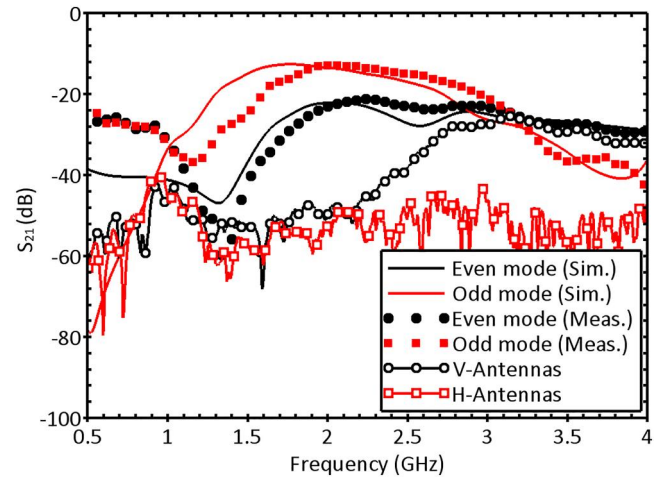


FIGURE 3 Simulated (Sim.) and measured (Meas.) transmission for the even and odd modes supported by the Spoof Surface Plasmon Polariton Transmission Line (SSPP TL). Line-Of-Sight (LOS) transmission measured in free space between vertically oriented (V-Antennas) and horizontally oriented (H-Antennas) antennas

measured reflection coefficient (not plotted) showed that the impedance matching of the antenna is frequency shifted down to 2.5 GHz for the odd mode, whereas it is kept to 3.14 GHz for the even mode. Whatever the mode, the maximum return loss was not affected by the coupling with a value higher than 20 dB at the resonance frequency.

Due to the radiation pattern, a very low transmission ($S_{21} < -40$ dB) is measured in free space in the whole measured frequency band when the dipole antennas are horizontal. If we compare the highest transmission values for the even and odd modes with the highest values for free space propagation, a 12-dB transmission improvement is achieved with the SSPP TL for horizontal antennas, whereas the

transmission is slightly increased by 4 dB for vertical orientation. Now focussing on an operation at 2.45 GHz, we can see that the SSPP TL allows to achieve a much higher transmission than in free space whatever the dipole antenna orientation. For the even and odd modes, the transmission enhancement is 16 and 37 dB, respectively. Together with the transmission enhancement, we can also note a size reduction of the antenna, which is shortened by 22% compared with a dipole antenna operating at 2.45 GHz in free space.

3 | PERFORMANCES FOR WBSN

As the resonance frequency can be tuned by changing the length of the dipole antenna radiating in free space, all the performances will be first compared to the maximum of transmission in free space, even though they are not achieved at the same frequency. That means performances of the even (odd) mode will be compared to $S_{21} = -25$ dB (-40 dB) measured in free space.

3.1 | Transmission dependence on the gap between antennas and TL

For evaluating the reliability of the wearable SSPP TL for on-body communication, transmission was first measured when the antennas were moved away from the SSPP TL. The measured transmission is plotted with g as a parameter in Figure 4a,b for the even and odd modes, respectively.

The gap g corresponds to the distance between the back side of the FR4 substrate supporting the dipole antenna and the SSPP TL. In Figure 4, the antennas were moved away from $g = 0$ (the back side of the FR4 substrate was in touch with the TL) up to $g = 10$ mm. Clear LOS transmission in free space is also plotted in Figure 4 for comparison when the SSPP TL was removed. As expected, when the gap g increases, the transmission decreases. For the even mode, the transmission level compared to the maximum in case of free space propagation is not degraded for a gap lower than $g = 2$ mm. On the other hand, the transmission for the odd mode is still higher than the highest transmission measured in free space (i.e., $S_{21} = -25$ dB for vertically oriented antennas) up to $g = 8$ mm. As the thickness of the substrate was 1.6 mm that means a distance of around 3 mm between the metallic pattern of the antenna and the TL can be considered as acceptable. In Figure 4a, we can see that the transmission measured for the even mode above 3 GHz is overlapped with the clear LOS transmission. Actually, for $f > 3$ GHz, the even mode is no more guided by the TL and transmission is related to a direct free space propagation between antennas, as it will be concluded later. A transmission dip at around 2.5 GHz is observed in Figure 4a for the even mode as a consequence of interference between the LOS transmission in free space and the guided wave launched by an antenna perpendicular to the SSPP TL. For $g = 0$ mm, the SSPP even mode mainly contributes to the transmission at 2.45 GHz and the contribution of the LOS transmission is

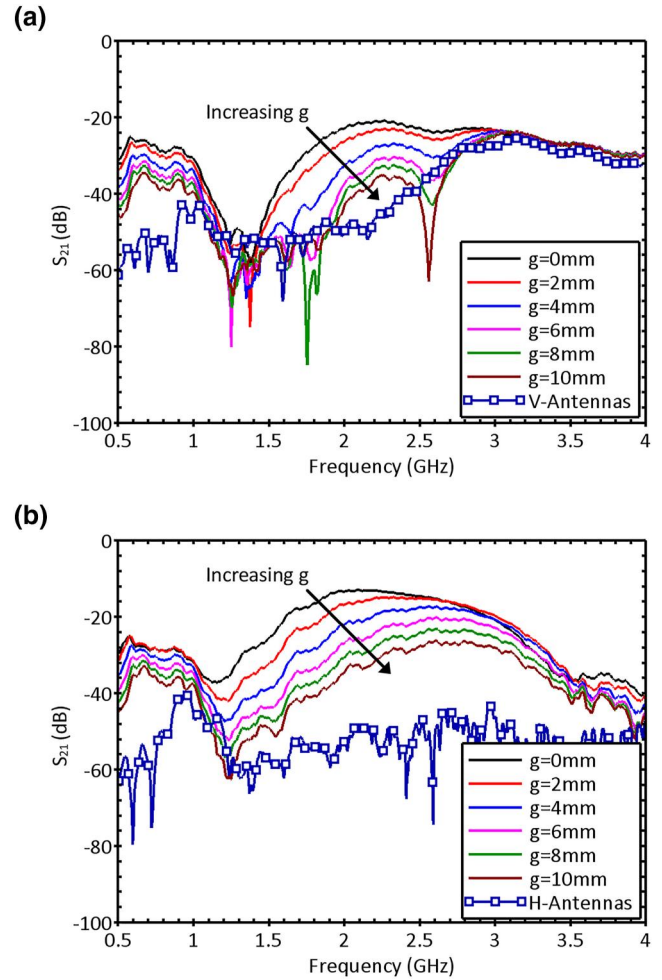


FIGURE 4 Measured transmission for the (a) even and (b) odd modes with the gap g between the antennas and the Spoof Surface Plasmon Polariton Transmission Line (SSPP TL) as a parameter. Line-Of-Sight (LOS) transmission measured in free space for two (a) vertically oriented (V-Antennas) and (b) horizontally oriented (H-Antennas) antennas

negligible. By increasing g , the part of the transmission due to the even mode decreases and it becomes comparable to the LOS transmission part for $g = 10$ mm. It results in a strong transmission dip shown in Figure 4a by destructive interference between the guided wave and the wave transmitted in free space. On the other hand, as the transmission in free space between horizontally oriented antennas is very low, the odd SSPP-guided mode exclusively contributes to the transmission and no transmission dip is observed in Figure 4b.

3.2 | Transmission dependence on antenna orientation

As previously shown, the even and odd modes are generated by a dipole antenna oriented perpendicular and parallel to the SSPP TL, respectively. Here, the influence on the transmission of a misaligned antenna is evaluated. Transmission was measured by considering the odd mode received by a

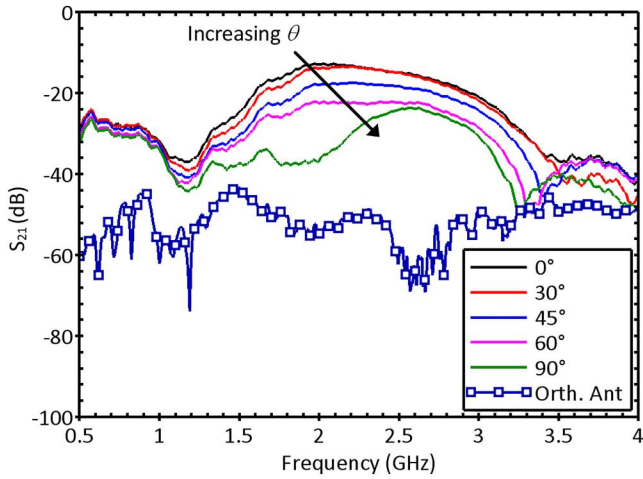


FIGURE 5 Transmission measured between a horizontally oriented antenna at Port 2 (odd mode received) and a rotated antenna at Port 1. $\theta = 0^\circ$ is for the horizontally oriented antenna (odd mode launched) at Port 1 and $\theta = 90^\circ$ is for the vertically oriented antenna (even mode launched). Line-Of-Sight (LOS) transmission measured in free space between two antennas with orthogonal orientations

horizontally oriented antenna at Port 2, whereas the antenna at Port 1 was rotated from $\theta = 0^\circ$ (horizontally oriented antenna) to 90° (vertically oriented antenna). Experimental results are plotted in Figure 5 with the clear LOS transmission measured in free space between two antennas with orthogonal orientation for comparison.

At 2.45 GHz, transmission (-15 dB) is unchanged for an incorrect orientation of the antenna lower than 30° and then gradually decreases down to -25 dB for $\theta = 90^\circ$. However, the lowest transmission achieved for $\theta = 90^\circ$ is still comparable to the transmission for the even mode supported by the SSPP TL ($S_{21} = -22$ dB) and for free space propagation between two parallel antennas as shown in Figure 4a. In Figure 5, transmission for $\theta = 90^\circ$ is enhanced by 30 dB at 2.45 GHz compared with the transmission in free space measured between two antennas with orthogonal orientations.

3.3 | Transmission under curvature and bending

Transmission was measured when the SSPP TL was curved with a radius of curvature $R = 10$ cm and when it was at right angle bent in the centre of the TL. Experimental results under curvature and bending were similar and only the results for the bent SSPP TL is shown as the worst case. The experimental setup is illustrated in the inset of Figure 6 for the even mode propagation with vertically oriented antennas. The antennas were positioned in order to maintain the length of the SSPP TL between antennas of around 25 cm yielding an LOS distance of 18 cm between antennas.

For the odd mode, the antennas were only rotated by 90° (horizontal orientation). The SSPP TL was bent by means of a dielectric foam (hidden by fabric in the inset of Figure 6). The

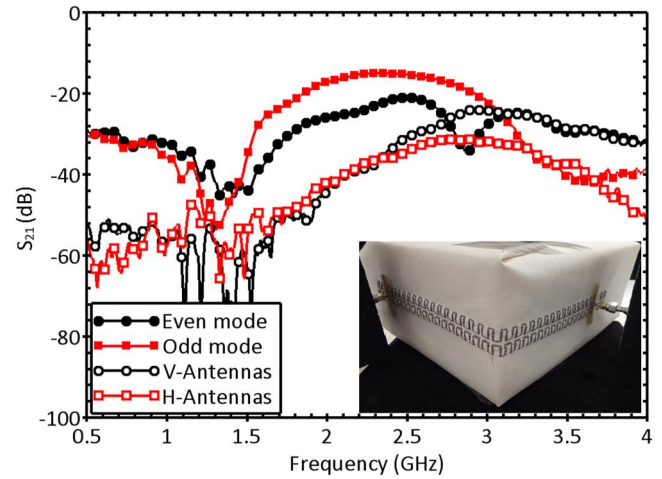


FIGURE 6 Transmission for the even and odd modes measured when the Spoof Surface Plasmon Polariton Transmission Line (SSPP TL) is bent. Line-Of-Sight (LOS) transmission measured in free space for vertically oriented (V-Antennas) and horizontally oriented (H-Antennas) antennas. In the inset, illustration of the experimental setup for SSPP TL under bending

transmission measured for the even and odd modes is plotted in Figure 6 with the corresponding transmission in free space when the SSPP TL was removed. Compared with the transmission measured for a straight SSPP TL shown in Figure 3, transmission is not degraded under bending and a higher transmission than in free space is still measured with $S_{21} = -21$ and -15 dB at 2.45 GHz for the even and odd modes, respectively.

For the sake of comparison, the clear LOS transmission measured in free space for both horizontally- and vertically oriented antennas is plotted in Figure 6. A lower transmission for the horizontal orientation of the antennas is a consequence of the radiation pattern of the dipole antennas. In the context of on-body communication, the LOS transmission through a body would be reduced because of high wave attenuation by human tissues [7–9]. Therefore, we can guess that the on-body transmission should be greatly improved using the SSPP TL.

3.4 | Transmission dependence on human body proximity

Performances degradation due to human body proximity was experimentally assessed by considering both an arm and a copper plate as obstacles between antennas. The obstacles were positioned inside a tunnel shaped by a semi-rigid paper with a radius of curvature of $R = 7$ cm. Then, the SSPP TL was fixed on the paper with adhesive tape. Such an experimental setup was considered to mimic a propagation around the human body between the back and chest when surrounded by the SSPP TL. A top view of the experimental setup is illustrated in the inset of Figure 7. The antennas face each other and they are oriented in horizontal and vertical direction for the even and odd modes, respectively. The LOS distance between antennas was $2R = 14$ cm and the antennas were

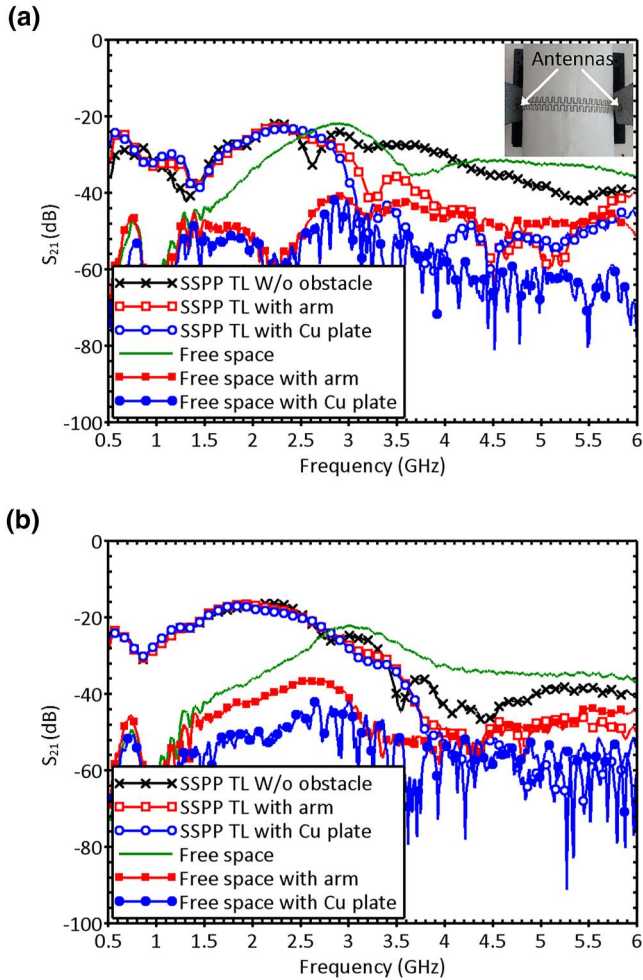


FIGURE 7 Measured transmission for the (a) even and (b) odd modes without (W/o) obstacles and for Spoof Surface Plasmon Polariton Transmission Line (SSPP TL) surrounding an arm or a copper plate positioned within a tunnel. In the inset, the experimental setup with curved SSPP TL with the antennas on each side

positioned in order to maintain a length of the SSPP TL between the antennas, that is, around 25 cm.

The measured transmission for the even and odd modes and with or without obstacles inside the tunnel is plotted in Figure 7. Measurements of the clear and obstructed LOS transmissions in free space are also plotted in Figure 7 for comparison.

In Figure 7a, the transmission dip observed at 2.6 GHz for the SSPP TL without obstacles emerges from the interference of the even-guided mode with the clear LOS transmission in free space as previously analysed in Section 3.1. When the arm or the copper plate is introduced in the tunnel between the antennas, the transmission dip vanishes because the obstacle drastically reduces the obstructed LOS transmission. As a consequence, the guided wave solely contributes to the transmission and no interference is observed. Cancellation of the LOS transmission by the arm and the copper plate is also observed in Figure 7 at higher frequency. For $f > 2.8$ GHz, a strong decrease of the transmission is observed in Figure 7a for the SSPP TL with the arm and the copper plate, whereas a high

transmission is sustained for the SSPP TL without obstacles. This is a confirmation of the previous expectation that the transmission above 3 GHz plotted in Figure 4a was sustained by the clear LOS transmission between the antennas and it was no more related to the even mode guidance. Here, the arm or the copper plate in the tunnel reduces the LOS transmission above 2.8 GHz and reduces the bandwidth for the even mode as a consequence.

Except the transmission dip, the transmissions measured with and without obstacle overlap for each of the modes when $f < 2.8$ GHz. Moreover, transmission is neither degraded by the arm nor by the copper plate obstacle with a maximum of S_{21} for the even mode (-22 dB) and the odd mode (-16 dB) as shown in Figure 7a,b, respectively. Also, we can note that the maximum of transmission for the even mode is comparable to the maximum of the clear LOS transmission in free space and the transmission is even slightly higher for the odd mode. Therefore, it is evidenced that the obstacle is bypassed by means of the SSPP TL whatever the dipole antenna orientation together with a transmission comparable or slightly higher to the highest value of the clear LOS transmission measured for two parallel antennas. Finally, the transmission enhancement by the SSPP TL in presence of the arm or the copper plate is first evaluated in the frequency band $f < 2.8$ GHz by comparing the highest transmission measured for a guided mode and the highest value of the ad hoc transmission measured in free space. For comparison with the even mode, $S_{21_max} = -41$ dB at 2.8 GHz is measured in Figure 7a for free space propagation with both arm and copper plate. For comparison with the odd mode, $S_{21_max} = -37$ dB is measured in Figure 7b for the free space propagation with the arm and $S_{21_max} = -42$ dB with the copper plate. With these values, it results in the transmission being improved by 19 dB for the even mode with both the arm and the copper plate, whereas the transmission enhancement for the odd mode is 21 dB with the arm and 26 dB with the copper plate. Now, if we focus on an operation at 2.45 GHz, the obstructed LOS transmission with a copper plate between antennas is lower than -45 dB and the transmission is improved by 22 dB for the even mode and 25 dB for the odd mode. These results confirm the reliability of embroidered SSPP TL in order to improve the transmission performances for on-body communication.

4 | CONCLUSION

An embroidered SSPP TL has been considered in order to improve transmission around the human body for WBSN application. The SSPP TL consists of two parallel meander-shaped strips, which support two propagation modes. Then, the even and odd modes have been launched by means of a dipole antenna oriented perpendicular and parallel to the TL, respectively. Correct fit has been shown between simulation and experiments for both dispersion curves and transmission before considering different possible alterations during on-body communication. Compared with the clear LOS transmission, a 16 dB and up to 37 dB transmission enhancement

has been measured at 2.45 GHz for the even and odd modes, respectively. The measured transmission has been sustained higher than the LOS transmission by moving the antennas lower than 3 mm away from the TL or by incorrectly orientating one of them up to 30°. Then, no transmission degradation has been observed for the SSPP TL under curvature and bending. Finally, transmission performances around the human body have been evaluated under curvature and by considering an arm and a copper plate as obstacles. A bandwidth decrease of the transmission for the even mode has been evidenced when the copper plate stops the LOS transmission for $f > 3$ GHz. However, a transmission enhancement higher than 22 dB at 2.45 GHz has been measured for both the even and odd modes when compared with obstructed LOS transmission with a copper plate obstacle between antennas.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The author elects to not share data.

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