On the Moisture-Resilience of On-Body Surface Wave Single Wire Transmission Lines (SWTLs)

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***Abstract*—Radio Frequency (RF) surface wave transmission lines support low-loss on-body propagation, and have recently attracted significant interest for wearables. In this work, the effect of fabric moisture absoption on a surface-wave textile Single Wire Transmission Line (SWTL) is analyzed in the Ultra High-Frequency (UHF) spectrum from 0.5 to 4 GHz. It is shown that moisture can increase the losses (in dB) by four-fold. The 42 cm SWTL maintains an insertion loss around 15 dB up to at 2.4 GHz, when the substrate is covered fully in water. The measured response is compared to a printed textile microstrip line; the surface-wave SWTL exhibits a more linear response to the moisture content indicating its suitability for RF moisture sensing applications.**

I. Introduction

Low-loss Radio Frequency (RF) links continue to represent a major research challenge hindering the full realization of wearable Body Area Networks (BANs) [1]. On one end, on-body radiative antennas have the advantage of spacial freedom but suffer from a low channel gain due to absorption and 3D spherical spreading. On the other end, low-frequency non-radiative means such as magneto-inductive wave-guides and capacitively-coupled Human Body Communication (HBC) offer a low loss [2], [3], but are limited to narrow and often low frequency bands [3].

Conformable surface wave propagation along the human body has recently attracted interest due to its ability to reduce the spreading loss [4]. Single Wire Transmission Lines (SWTLs) represent a low-complexity structure which could support surface wave propagation in harsh environments [5] and is compatible with simple e-textile fabrication techniques [6]. While wearable SWTLs exhibit an improved immunity to discontinuities compared to microstrip lines [6], their performance when loaded with a lossy dielectric, e.g. moisture and sweat, remains unknown.

In this paper, a state-of-the-art textile-based SWTL is investigated under moisture-loading and its transmission properties are compared to a conventional textile-based microstrip line. It is observed that for high moisture contents the SWTL exhibits lower attenuation. Moreover, the SWTL's linear S_{21}/moisture relation presents it as a candidate for RF moisture sensors.

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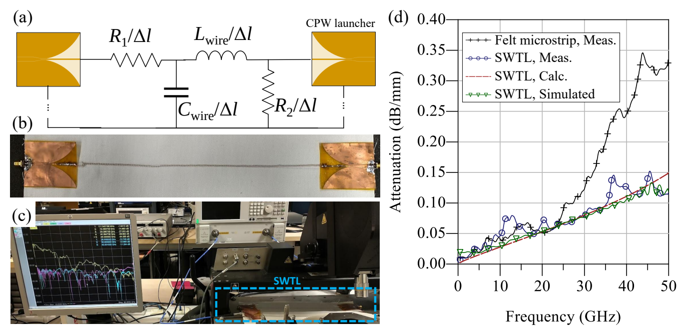

Fig. 1. The wearable textile SWTL: (a) layout and launchers; (b) prototype photograph with the shielding fabric underneath; (c) 50 GHz PNA measurement setup; (d) line attenuation compared to a microstrip line on a felt substrate from [7].

II. Textile SWTL Design and Characterization

The textile SWTL investigated in this work is based on an over-stitched "e-textile" wire of a 40 µm radius on a polyester cotton substrate. On the fabric's bottom layer, a shielding conductive fabric is added to eliminate the losses introduced by human proximity [6]. Fig. 1 shows the SWTL's equivalent circuit per unit length, photograph of the prototype and measurement setup using an Agilent PNA Vector Network Analyzer (VNA), and the measured attenuation normalized to the line's length. The attenuation is compared to printed textile-based microstrip line, on a felt substrate, from [7] in its pass-band. The SWTL is approximately 42 cm-long, with limited deviation from a straight line due to fabrication tolerances, and the feed is based on tapered coplanar waveguide launchers whose dimensions are in [6]. Using an analytical capacitance and inductance of a wire model [8], the SWTL maintains a Z_0=210.4 Ω. Owing to the higher Z_0 and reduced conductor losses, the SWTL maintains a lower loss than a Quasi-TEM 50 Ω microstrip line as in Fig. 1(d).

III. Effect of Moisture on Transmission

The s-parameters of the SWTL were measured for varying moisture content, where approximately 1 ml drops of tap water were added onto the line. Fig. 2 shows the measured $|S_{21}|$ and $|S_{11}|$ response of the water-loaded SWTL. From the S_{21} response, it can be seen that the attenuation in the line increases with increased water-content, which is attributed to the high conductivity of tap water acting as a lossy dielectric. However, as the SWTL's impedance matching takes place

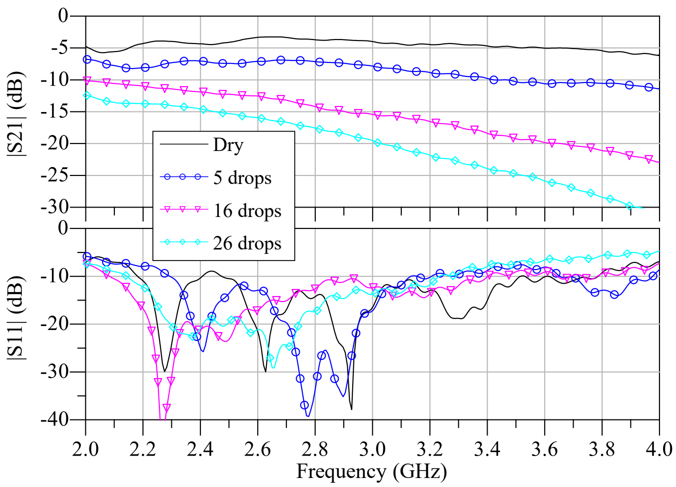

Fig. 2. Measured s-parameters of the SWTL for different moisture contents.

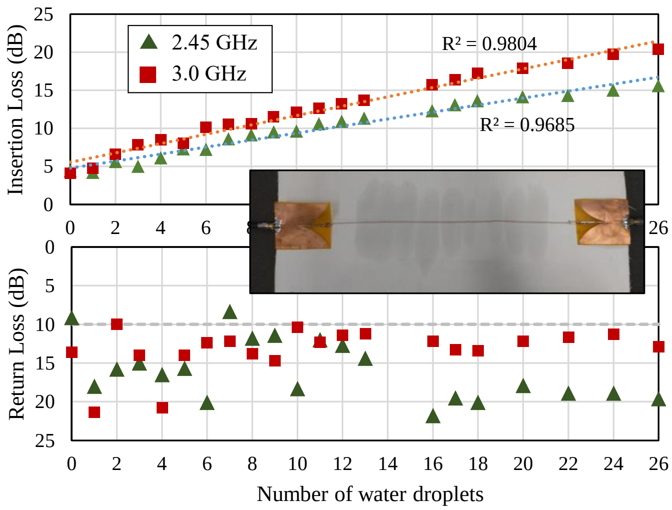

Fig. 3. Measured insertion and return loss of the shielded textile SWTL in response to added moisture, showing a linear increase in the insertion loss with a matched return loss

mostly at the Coplanar Waveguide (CPW) tapered launchers, it maintains a mostly consistent minimum return loss of 10 dB, as seen from the $|S_{11}|$ in Fig. 2.

To precisely quantify the effects of moisture on the attenuation and to compare the SWTL to the felt-based printed microstrip line, the insertion and return loss of both the SWTL and microstrip are shown in Fig. 3 and 4, respectively, as a function of the added water content. The results are reported at 2.4 and 3 GHz, which represent the license-free band and the lowest frequency in the UWB band, respectively.

Observing the insertion loss of the SWTL, it can be seen that the losses increase almost linearly with added moisture. Not only does this response makes the SWTL's behavior more predictable, but also enables the SWTL to be used as a wearable moisture sensor. The matched return loss indicates the suitability of the SWTL for applications requiring a low standing wave ration even when loading with water.

On the other hand, while the microstrip line exhibits a lower loss initially, owing to its shorter length of 7 cm compared, its

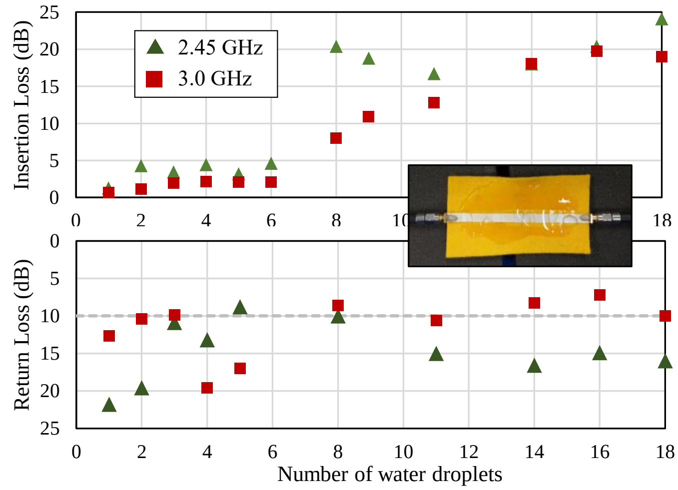

Fig. 4. Measured insertion and return loss of the Z_0=50 Ω printed microstrip line on a felt fabric substrate, showing a mismatched return loss for a higher water content.

insertion losses increase substantially once 8 drops of water are added. This could be attributed to the water droplets agglomerating and forming lossy resonant structure which absorbs the inserted signals, which is also reflected through the mostly maintained return loss.

IV. Conclusion

In this paper, the effect of moisture, in the form of fabric water-absorption, on a textile-based SWTL has been investigated experimentally in the UHF spectrum. It was shown that the SWTL exhibits a more uniform matched S_{11} compared to a microstrip line with lower losses when the water loading increases beyond approximately 20 drops. The highly linear response of the SWTL to moisture highlights its suitability as a wearable RF moisture sensor.

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