Connection Strategies for Wearable Microwave Transmission Lines and Antennas

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***Abstract*—In this paper a range of connection strategies are investigated for application to flexible passive microwave devices. The binding theme of all solutions is a simple manufacturing process and compatibility with textile materials. Three potential connection strategies are presented - snap-on buttons, butterfly clasps and wing solution. All the connection strategies are evaluated on a perpendicularly fed microstrip line. Based on the electrical performance, manufacturing complexity and mechanical stability, the best connection strategy is suggested for microwave applications in practical on-body environments.**

***Index Terms*—textile conductors, wearable electronics, flexible transmission lines, conductive fabrics**

I. INTRODUCTION

Wearable electronics is fast emerging as a major growth area with applications in healthcare, personal and military communications [1], [2]. An integral component of wearable electronic systems required for wireless communications are the antennas and associated transmission lines. Such interest has lead to a range of flexible passive microwave components ranging from flexible transmission lines [3]–[6], conductive textile antennas [7]–[10] to embroidered antennas [11]–[15].

Healthcare appears to be a focal point of wireless wearable electronics with the aim of removing the need for unwieldy wired monitoring systems. Wireless monitoring systems have the potential to enhance the quality of life for patients who may need consistent physiological monitoring, e.g patients in intensive care units or the elderly [1]. For such applications there are two main streams of antenna development, the first one using highly miniaturized but non-flexible antennas. The main limitation of using such antennas is their low efficiency and discomfort to the wearer. An alternative approach is to integrate the antenna into clothing using fully textile materials such as conductive fabrics and conductive threads.

Whilst there have been significant research interest in developing new antenna topologies for wearable applications, the realization of robust and efficient connections for the proposed antenna topologies is an area in early stages of development. Generally forming reliable connections to flexible microwave devices tend to be a challenging task as a transition from a flexible to a rigid device is required. A standard connection strategy for validation of textile microwave devices is through the use of conductive epoxy. Whilst being an elegant solution for verification of prototypes, conductive epoxy can break after repeated bending, rendering these type of connections unusable in a practical setup.

Towards better applicability in the context of textile antenna connections, investigations have been performed aimed at using snap-on buttons as alternative radio-frequency connectors. A dedicated snap-on connector presented in [16] was operated up to 3 GHz and shown to be immune to extreme bending which might be experienced by a device worn by a human. As an alternative to the work presented in [16], commercial snap-on buttons were used in [17] as a replacement to coaxial connectors for a coaxial to microstrip transition. Measured results showed that the connectors provided suitable performance up to 3 GHz, (similar to that of the dedicated connectors). Recently, commercial snap-on buttons have been investigated for forming reliable and detachable connections for RFID tag antennas [18] where it was shown that the snap-on buttons do not significantly alter the return loss of a textile wideband dipole antenna allowing them to be used in practical situations.

An alternative connection mechanism was explored in [19] using hook and loop connectors. It was shown that whilst hook and loop connectors can provide a reliable connection, the hook and loop connectors introduced significant losses into the structure which can be improved by electroplating the hook and loop connectors.

In the present work three connections strategies are investigated for connecting the inner pin of a SMA connector to a textile transmission line. A central theme of the proposed solutions is that they are all commercially available with minimal manufacturing complexity. The connection strategies investigated are conductive epoxy, snap-on buttons, butterfly clasps and wing solution. The connection strategies will be compared on the basis of their electrical performance, ease of manufacturing and applicability to practical on-body scenarios.

Whilst the connections strategies are evaluated on transmission lines they can also be applied to antennas.

II. OVERVIEW OF TRANSMISSION LINE AND CONNECTION STRATEGIES

A. Transmission Line

The structure to be tested is shown in Figure 1. It consists of a 50 Ω microstrip line with back to back connections to SMA connectors. The relevant dimensions are L_t = 37.5 mm, d = 2 mm, W_l = 7.5 mm on a ground plane of width 50 mm (W_s) and length 60 mm (L_s) . The substrate has a thickness h_1 = 1.6 mm and a relative permittivity of $\epsilon_r = 1.06$. The length of the transmission line L_t is chosen as small as possible to minimize resonant effects arising due to reflections

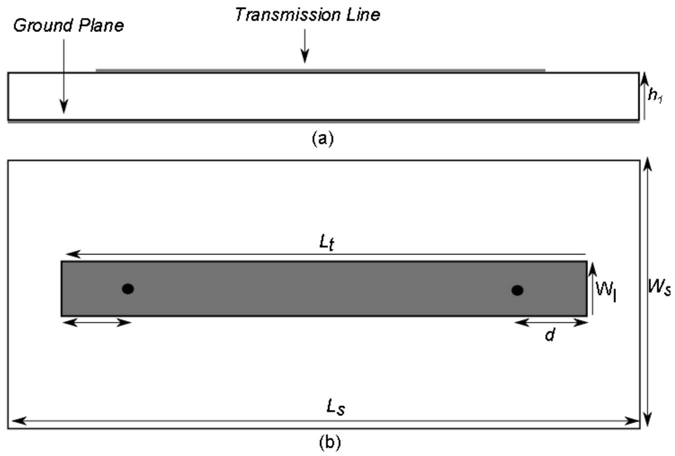


Fig. 1: Geometry of the Through-fed 50 Ω Microstrip line (a) Side View, (b) Top View.

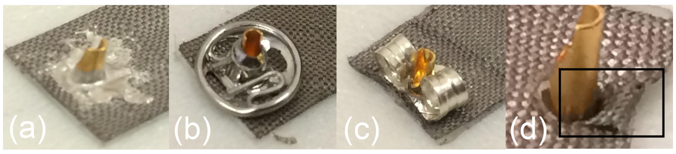


Fig. 2: Investigated connection strategies, showing from left to right, conductive epoxy, snap-on buttons, butterfly clasps and wing solution.

from either end of the transmission line. As a trade-off between electrical performance and manufacturability the distance d was chosen as 2 mm.

The four connection strategies to be investigated, depicted in Fig 2, are described in the next section.

B. Connection Strategies

The simplest and most widely employed strategy is the use of conductive epoxy (Fig. 2a). In this strategy a thin layer of conductive epoxy is applied at the contact area between the inner pin and the transmission line. Conductive epoxy can be viewed as a replacement for solder as the heat required during soldering would weaken the structural integrity of fabrics making them prone to breaking. For maximum bond strength and conductivity, conductive epoxy requires 24 hour set time leading to an extended manufacturing time.

An alternative strategy is through the use of snap-on buttons (Fig. 2b). In this strategy the inner pin is tightly clasped by the snap-on buttons, while simultaneously the button tightly holds onto the textile transmission line thus increasing the contact area. The snap-on buttons can be thought of as a textile rivet, and the specific fabrication procedure will be elaborated in Sec. III.

As a different type of pressure contact, butterfly clasps were investigated, as commonly used for ear-rings. In this solution the looped arms of the clasp tightly hold the pin which can then be pressed onto the substrate (Fig. 2c). Whilst this proves to be a feasible solution, the main disadvantage comes from its non planar structure. This can however be remedied by compressing the clasp whilst providing a good mechanical connection to the inner pin. Care has to be taken when compressing the clasp to ensure that the arms remain functional. In addition, due to the mechanical pressure of the clasp the substrate might become slightly compressed, which may affect transmission properties.

The final investigated strategy that relies on pure pressure contact is provided by the "wing solution". In this structure two additional tails are realized in the fabric. The inner pin of the SMA connector is then removed with the tail being passed through the teflon body of the SMA, the pin is then inserted back in and remaining silver fabric is trimmed down. The advantage of this solution is that the connection mechanism is hidden, thus it offers greater protection against hostile environmental influences such as bending.

III. MANUFACTURE

Four prototypes of the textile microstrip line with back-to-back connections shown in Fig. 3 were manufactured. The conductive ground and signal layer were both manufactured from ShieldIt NSC95R-CR fabric with an empirically determined sheet resistance of 0.04Ω/□ [5] whilst the substrate was made from PF4 (Cuming Microwave Corporation) a highly flexible low loss radome foam, with ϵ_r = 1.06, tanδ = 0.0001 and thickness h_1 = 1.6 mm. Attachment of the conductive fabric to foam was done through double sided adhesive. The basic manufacturing procedure can be summarized as follows

- Cut out ground, signal and substrate layers.
- Cut out hole in ground plane and substrate to accommodate SMA connector.
- Cut out hole in signal layer for inner pin to protrude through.
- Use double sided adhesive to bond silver fabric to foam.
- Attach SMA connector with conductive epoxy.

Considering now the manufacture of the snap-on buttons, a specific procedure is outlined in Figure 4. In this set-up the male portion of the snap-on buttons is first trimmed down to leave only the inner tubing (Fig. 4b). This is to prevent short circuiting the SMA connector. This inner tubing can then be riveted through the substrate (Fig. 4c). The inner pin of the SMA is then passed through the inner tube at which point the female portion of the button is placed on top to mate with the male portion leading to a proper connection (Fig. 4d). For the butterfly clasp prototype the additional manufacturing step is to press on the clasp after following the basic procedure mentioned above. The manufacturing procedure for the wing solution is depicted in Figure 5. In this case, additional narrow tails should be realized in the transmission line. To easily pull the tail through the SMA connector hole a tail length of several centimeters is recommended.

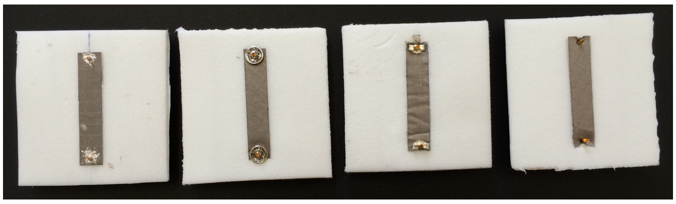


Fig. 3: From left - conductive epoxy, snap-on buttons, butterfly clasp, wing solution.

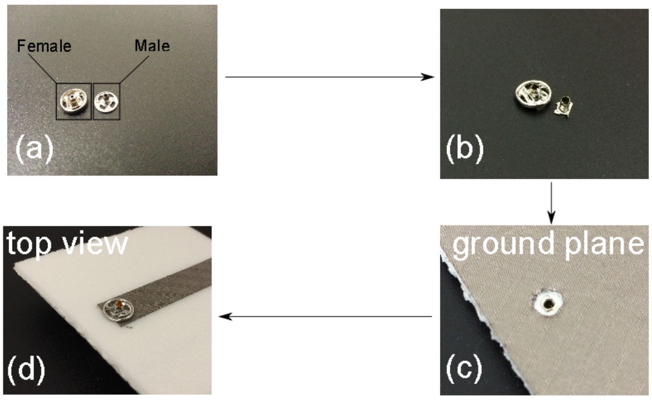


Fig. 4: Snap-on buttons manufacturing procedure.

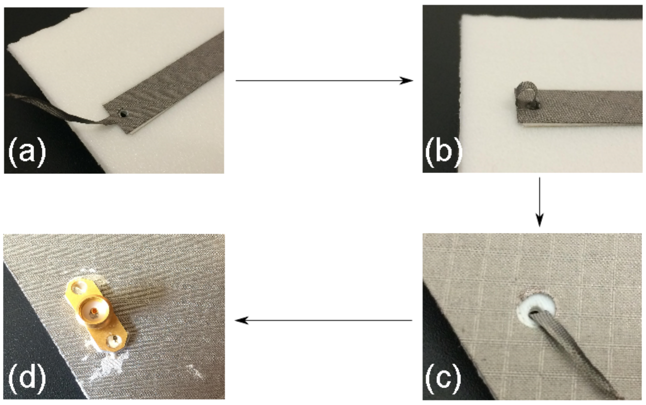


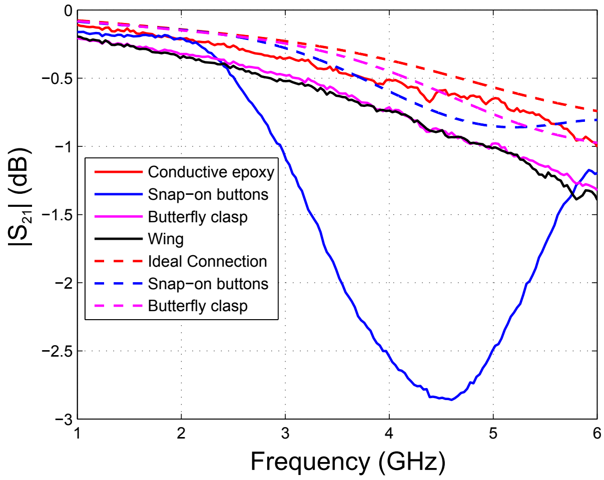
Fig. 5: Wing solution manufacturing procedure.

IV. COMPARISON OF STRATEGIES

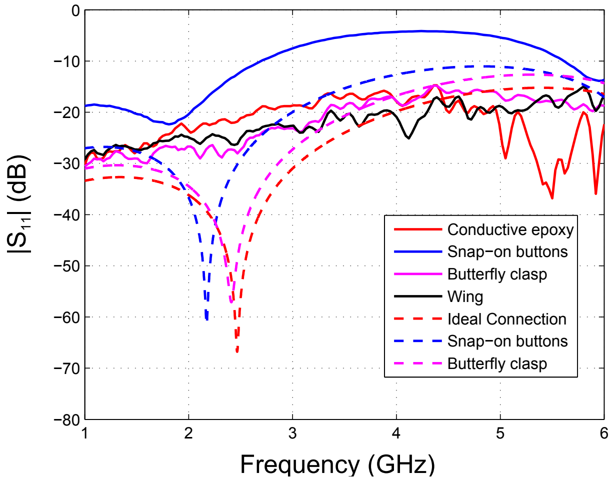
A. Electrical Performance

As all the proposed strategies modify the nominal geometry they were separately modeled in ANSYS HFSS. The snap-on buttons can be modeled by a hollow cylindrical tube through the substrate, representing the male portion, and a cylindrical object with a spherical bulge, representing the female portion as demonstrated in [18]. The butterfly clasps can be accounted for by two hollowed cylindrical objects pressing against the pin. Finally, the wing solution can be simulated by a thin strip of silver fabric running down the length of the inner pin, wedged in between the center pin of the coax and the outer teflon.

To test the performance of the connection strategies the reflection coefficient and the transmission coefficient were measured using a network analyzer. The simulated (dashed) and measured results (solid) are compared in Fig. 6. It can be observed that the ideal connection provides suitable performance up to at least 6 GHz, with a reflection coefficient below -15 dB and a transmission coefficient above -0.7 dB. As can be expected, the transmission progressively degrades at higher frequencies because of increasing losses, as visible in Fig. 6a. The simulated results with conductive epoxy and the wing solution have been omitted as they are highly similar to the ideal connection.



(a) Transmission Coefficient



(b) Reflection Coefficient

Fig. 6: Simulated and Measured Results.

The most pronounced discrepancy is the lower than predicted transmission coefficient for all measured prototypes. In simulations the silver fabric was modeled with an empirically determined sheet resistance of $0.04\Omega/\square$ where fabric glue was used for the bonding agent. In the present work double sided adhesive was used. At higher frequencies this discrepancy becomes more pronounced as the double sided adhesive starts to act as a lossy dielectric layer of non-negligible thickness.

Referring to (Fig. 6a) it can be seen that the measured transmission coefficient for the structure using conductive epoxy is in good agreement with the nominal result. For snap-on buttons however the measured results show an obvious discrepancy, this is largely attributed to the severe compression effects of the snap-on buttons. A slight discrepancy is noted for the butterfly clasp which can also be attributed to a slight compression of the substrate. Finally the wing solution shows a lower transmission coefficient than the nominal solution, which is attributed to fabrication tolerances.

The measured reflection coefficient generally shows good agreement with the simulated results with the exception of the snap-on buttons. This is once again attributed to compression effects resulting in a mismatch at higher frequencies.

B. Applicability to practical scenario

The conductive epoxy, whilst providing excellent agreement between simulated and measured results, is not suitable for practical applications. Intrinsically conductive epoxy is not meant to be flexible thus repeated bending of the structure (due to human body movements) can crack the conductive epoxy.

Whilst snap-on buttons can be used, the design must account for the altercations in the geometry. Additionally, compression effects must also be considered when using the snap-on buttons as these become more pronounced at higher frequencies.

Unfortunately the butterfly clasp is rather easily dislodged via environmental pressure (i.e patient movements). In such a situation the arms of the clasp may move apart slightly leading to a poor connection. Whilst this can be remedied by pushing the arms back together, repeated pressure on the arms can break the arms rendering the connection unusable.

Whilst offering similar electrical performance to the conductive epoxy, the wing solution provides greater mechanical stability as breaking the connection requires dislodging the inner pin of the SMA connector. Economically this solution stands out as it requires no additional components, unlike the other three solutions).

V. CONCLUSIONS

A range of textile connection strategies have been presented and compared on the basis of electrical performance and practical applicability. It is noted that of the four connection strategies investigated, two proposed connection strategies, snap-on buttons and butterfly clasps have a non-negligible impact on electrical performance which needs to taken into account. On the merits of minimal effect on electrical performance, mechanical stability, economic viability and manufacturing simplicity the wing solution is suggested as a viable alternative to the standard connection method, namely conductive epoxy.

VI. ACKNOWLEDGMENT

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