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RESEARCH PAPER

On the development of a novel high VSWR programmable impedance tuner

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Impedance tuners are key instruments used for load- and source–pull measurements. They are crucial for any active microwave components, circuits, and systems characterization and optimization. This paper reports theoretical, simulated, and experimental results related to the development of a novel programmable impedance tuner offering high-voltage standing wave ratio (VSWR). After presenting the proposed tuner principle, a fabricated prototype operating at microwave frequencies and based on a 3.5 mm coaxial line is introduced with experimental results. Depending on the targeted frequency band, different pairs of slugs, with optimized length and characteristic impedance, can be used to obtain an optimal VSWR. This first prototype allowed us to demonstrate the interest of the proposed impedance synthesis principle and to identify ways forward to further improve its performances and push forward this promising technology.

Keywords: Coaxial line, High VSWR, Impedance tuner, Load–pull, Measurement, Microwave, Slug, Source-pull

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I. INTRODUCTION

Impedance tuners are key instruments used for the characterization and load- /source-impedance optimization of active components, circuits, and systems. They are used for example for transistor characterization [1], power amplifier design [2], low-noise amplifier design [3], and oscillator measurement [4]. They could also be used to determine optimal impedances of more complex integrated circuits [5]. Passive, active, and hybrid tuner technics are found in literature [6]. The type of required measurement will determine the tuner choice [7]. Passive tuners have many advantages, including rapid impedance synthesis, relatively higher-power handling capability, measurement of high-power devices without any non-linear effect, ease of usage, low maintenance cost, relatively low implementation cost, and the absence of any oscillation [6]. They are commercially available from Focus Microwaves [8] and Maury Microwave [9]. Their principle is based on sliding carriages along a transmission line and vertically positioned RF probes. The main disadvantage of such passive tuners is that they do not allow one to achieve very high-voltage standing wave ratio (VSWR) to synthesize impedances located nearby the Smith chart outer boundary [6].

AdvTech and the IMS Research Center are developing and characterizing an original high-performance programmable coaxial impedance tuner that is presented in this paper. Early results were introduced in [10]. This tuner is of particular interest to achieve very high VSWR. It will allow component and circuit designers finding optimal source and load impedances, when located close to the Smith chart outer boundary.

Section I will introduce the operating principle of the proposed tuner. Then a fabricated prototype will be introduced in Section II. Finally, Section III presents the experimental results. Compared with [10], this paper provides a better understanding of the prototyped tuner with improved connections and an identification of ways to further improve performances.

II. OPERATING PRINCIPLE

The developed high VSWR impedance tuner original concept was proposed for the first time by Vellas *et al.* [11]. It was based on two short-length low characteristic impedance coaxial sections (called slugs) independently sliding along a 50 Ω coaxial transmission line. However, due to the implemented slugs' positioning mechanism, prototypes based on this original concept never allowed one to experimentally demonstrate the expected theoretical performances due to the breakage of mechanical elements and poor repeatability. The required clearance, between the slugs' outer boundary and the main coaxial transmission line outer conductor, allowing slugs displacement within the main coaxial line, provided a poor electrical contact between those two parts. Furthermore, a good axiality of the different mechanical elements was very difficult to obtain.

An alternative solution based on an outer coaxial conductor composed of a fixed bottom part and movable upper part

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was proposed in [12]. With this approach, the main coaxial transmission line can be opened to allow the slugs' displacement, providing at the same time a low wear of the mechanical elements. When slugs are positioned, the main coaxial line is closed to provide a good electrical contact and perfect axiality at the same time.

Figure 1(a) illustrates the main coaxial line of Z_o characteristic impedance. Its important dimensions are D_C, the inner diameter of the outer conductor, and d_C, the diameter of the inner conductor (Fig. 1(b)). The two slugs, of inner diameter D_S and length L_S, inserted within the main coaxial line, results in a Z_S low characteristic impedance coaxial section (Fig. 1(c)). The two slugs can be independently slide along the main coaxial line. L_1 and L_2 are the length between the input and the first slug and in-between the two slugs, respectively.

The equivalent transmission line model is illustrated in Fig. 2. Varying L_1 and L_2 allows synthesizing desired impedance Z_{tuner} at the tuner input port. A schematic model on ADS from Keysight was used to validate the tuner principle. A closed-form equation of the impedance tuner reflection coefficient can be obtained considering successive stubs in series of length L_{stub_i}, impedance Z_{stub_i}, and propagation constant β_{stub_i} to transform an output impedance Z_{out_i} to an input impedance Z_{in_i} [13].

$$Z_{in\_i} = Z_{stub\_i}\left(\frac{Z_{out\_i} + jZ_{stub\_i}\tan(\beta_{stub\_i}L_{stub\_i})}{Z_{stub\_i} + jZ_{out\_i}\tan(\beta_{stub\_i}L_{stub\_i})}\right), \quad (1)$$

Figure 3 reports measured synthesized impedances on the Smith chart at 10 GHz using the prototype introduced in the next section. Figure 3(a) shows one of the impedance synthesis options. The first slug is positioned at a L_1 distance from the tuner input allowing one to change the circle center travelled on the Smith chart when displacing the second slug away from the first slug (increasing L_2). This way, the all Smith chart impedances can be synthesized. A second impedance synthesis option is illustrated in Fig. 3(b). The distance L_2 is fixed to obtain different circle radius on the Smith chart, and the L_1 distance is increased to synthesize impedance along the circle.

To design the proposed tuner, it is important to determine its main characteristics, including the characteristic impedances, single-mode frequency ranges, and transmission losses of the main coaxial line and slugs.

The characteristic impedance Z of the main coaxial line (Z_o) and of the short-length low characteristic impedance slugs (Z_S) are obtained using (2) [13]:

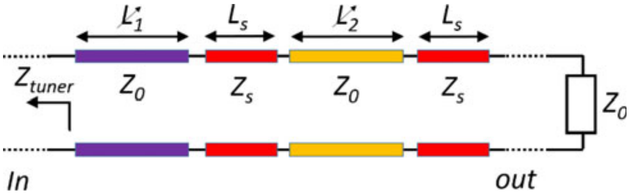


Fig. 2. Impedance tuner transmission line model.

$$Z = 138\log\left(\frac{D}{d}\right), \quad (2)$$

where D and d are the inner diameter of the outer conductor and the diameter of the inner conductor, respectively.

The single-mode frequency band of the fundamental transverse electromagnetic mode (TEM) mode of the coaxial line is limited by the TE_{11} modes which cut-off frequency f_{cTE11} is given by:

$$f_{cTE11} = \frac{2c}{\pi(D+d)}, \quad (3)$$

where c is the light velocity.

Taking into consideration air as dielectric, the attenuation constant α, neglecting surface roughness loss, and considering conductor loss, is obtained using:

$$\alpha = \frac{8.686}{2\times 138}\sqrt{\left(\frac{f\mu_o}{\pi}\right)}\left(\frac{\sqrt{\rho}}{D} + \frac{\sqrt{\rho}}{d}\right)\frac{1}{\log(D/d)}, \quad (4)$$

where f is the frequency, μ_o is the vacuum permeability, and ρ is the conductor resistivity.

As proposed in [12], the coaxial transmission line outer conductor can be divided in two parts to allow slugs' displacement. A view of the tuner mechanics is illustrated in Fig. 4 in opened and closed positions.

At the tuner input and output, 3.5 mm connectors are used to target a frequency band of operation up to 26.5 GHz. To avoid mismatch at the interconnection between the main coaxial line and connector, D_C is chosen at 3.5 mm, and (2) gives $d_C = 1.52$ mm to obtain a characteristic impedance $Z_o = 50\ \Omega$. Therefore, the single-mode frequency band of operation of the fundamental TEM mode is determined to be up to 38 GHz using (3).

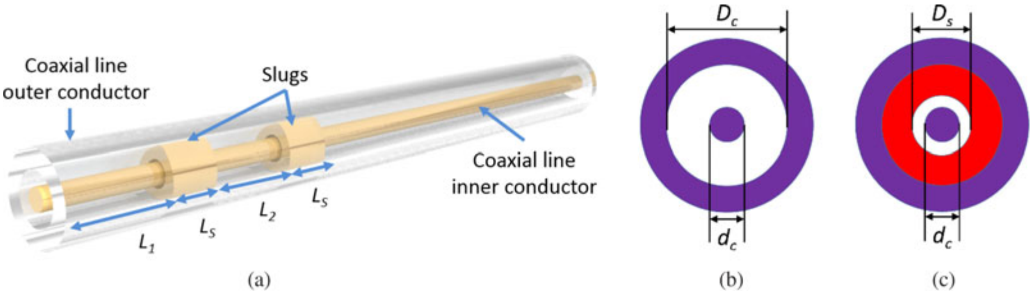
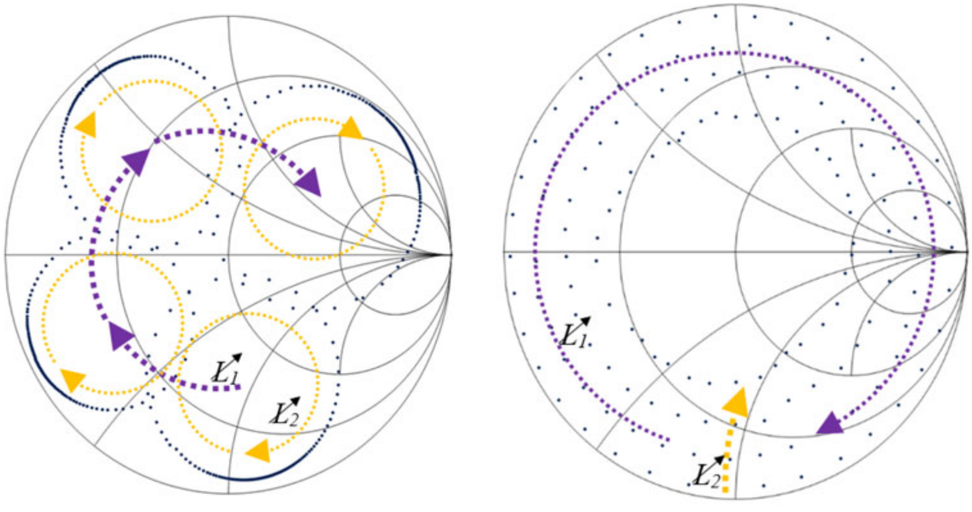
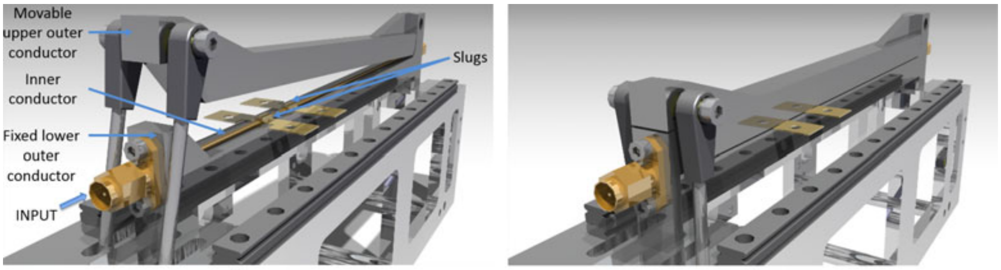


Fig. 1. (a) Illustration of the tuner principle with cross-sectional view of (b) the main coaxial line, and (c) the two coaxial slugs.



(a) (b)

Fig. 3. Measured synthesized impedances using (a) the first and (b) second principle at 10 GHz.



(a) (b)

Fig. 4. View of the proposed tuner in (a) opened and (b) closed positions.

For practical reasons, brass, with resistivity $\rho_{brass} = 6.67 \times 10^{-8}\ \Omega$.m, is used for the fabrication of the prototype. However, a low loss main coaxial line is desired to achieve very high VSWR. Plating the element with silver, $\rho_{silver} = 1.64 \times 10^{-8}\ \Omega$.m, with a thickness t_{silver} of at least three skin depth δ_{silver} at the lower frequency of operation can provide better performances. Considering a lower frequency of operation of 2 GHz, t_{silver} must be more than 4.3 μm. Using (4), at 15 GHz, transmission loss can be improved from 0.71 dB/m using brass to 0.35 dB/m using silver plating. The transmission loss improvement versus frequency obtained in simulation using HFSS from ANSYS is show in Fig. 5 for a 160 mm long main coaxial line. This figure also compares performances of the main coaxial line without and with two 400 μm slots on both sides resulting from the splitting of the main coaxial line in two parts. It can be observed that the two slots do not impact transmission loss.

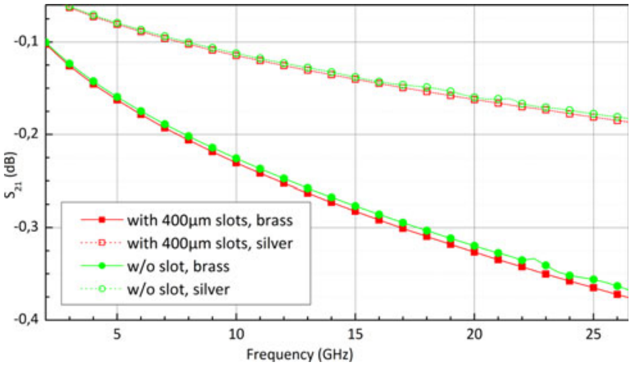


Fig. 5. Simulated S_{21} parameter of the 16 mm long 3.5 mm main coaxial line without and with two 400 μm slots using brass and silver conductors.

The transmission line model shown in Fig. 2, was implemented on ADS Schematic taking into account conductor loss and also the 18 mm long access coaxial line between the input connector and the main coaxial line. This access line length could be reduced redesigning the mechanics to reduced losses between the input connector and the slugs and therefore increase VSWR. A set of three slugs of length $L_S = 3$, 7, and 14 mm allows one to achieve high VSWR over the 2–26.5 GHz frequency range as shown in Fig. 6. Figure 6 also highlight the improvement in VSWR that can be achieved silver plating the conductors. In this figure, the minimum and maximum values of the maximum VSWR achieved around the Smith chart periphery (for all reflection coefficient angles on the Smith chart) are shown versus frequency. As L_1 and L_2 sections have losses, they decrease the

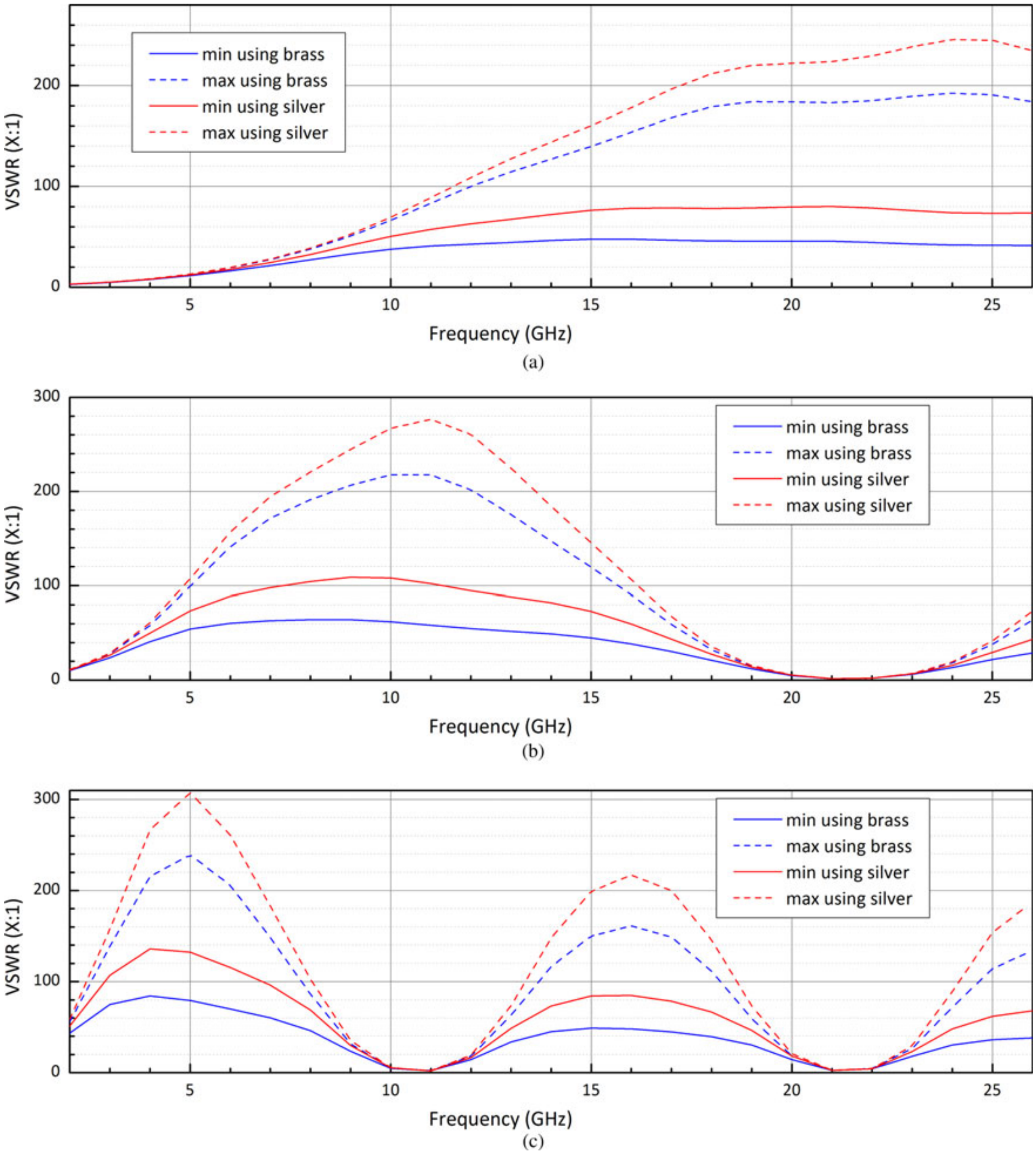


Fig. 6. Simulated maximum and minimum VSWR versus frequency for (a) $L_S = 3$, (b) 7, and (c) 14 mm long slugs using brass- and silver-plated conductors.

maximum VSWR. This also explains why the centers of circles shown in Fig. 3(b) do not appear to be centered at the Smith chart center.

Figure 7 shows the minimum values of maximum VSWR achieved around the Smith chart periphery versus frequency for $D_S = 1.8$, 2, and 2.2 mm corresponding to characteristic impedances $Z_S = 10.1$, 16.4, and 22.1 Ω, respectively. It can be seen that reducing the slugs sections characteristic impedances, higher VSWR can be reached. However, for practical reasons, D_S was limited to 1.8 mm in this study.

Figure 8 shows the return loss achieved for $L_S = 14$ mm long slugs with $Z_S = 10.1$ Ω versus normalized inter-slug distance $x = L_2/\lambda$ for the minimum value of L_1. It can be seen that for those slugs, the maximum VSWR is achieved for $L_2 \approx \lambda/3$, and that an impedance close to 50 Ω is synthesized for $L_2 \approx 2\lambda/3$.

III. FABRICATED IMPEDANCE TUNER

For demonstration purpose, a tuner based on the principle described in the previous section has been fabricated with $D_C = 3.5$ mm, $d_C = 1.52$ mm, and a total length of 160 mm. The fabricated prototype is shown in Fig. 9. The slugs' displacement is provided by ETEL linear motors associated with linear positioning ruler from Heidenhain achieving an accuracy as low as 4 μm. Figure 9(b) shows a detailed view of the fabricated tuner. The two brass slugs shown in Fig. 9(b) are 3 mm long. The mechanical tuner design allows operators to manually change slugs in <10 min. This permits to optimize the tuner performances during measurement in a given frequency range.

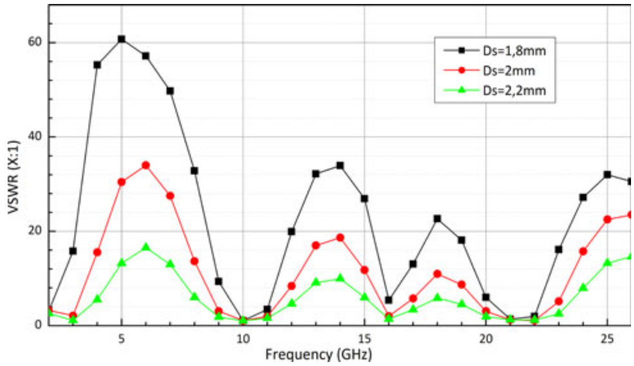


Fig. 7. Simulated minimum VSWR versus frequency for 3 mm long slugs with $D_S = 1.8$, 2, and 2.2 mm using brass.

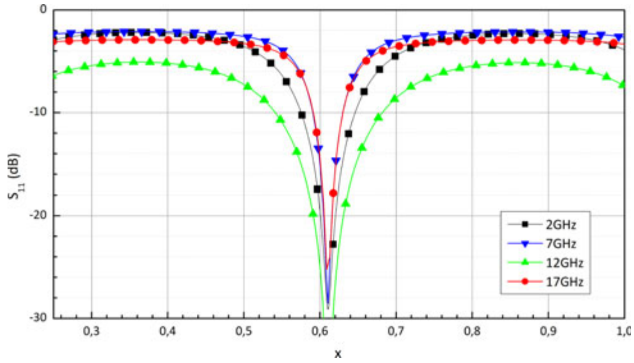


Fig. 8. Simulated S_{11} parameter versus normalized inter-slug distance $x = L_2/\lambda$ for $D_S = 1.8$ mm and a $L_S = 14$ mm long slugs.

Figure 10 shows the measured S_{21}-parameter of the tuner without slugs. In [10], return loss and transmission loss performances were limited by the implemented 3.5 mm connector that did not provide a good matching. A new 3.5 mm connector has been implemented to achieve good performances up to 26.5 GHz. This new 3.5 mm connector has been machined to achieve a better electrical contact with the coaxial line outer conductor.

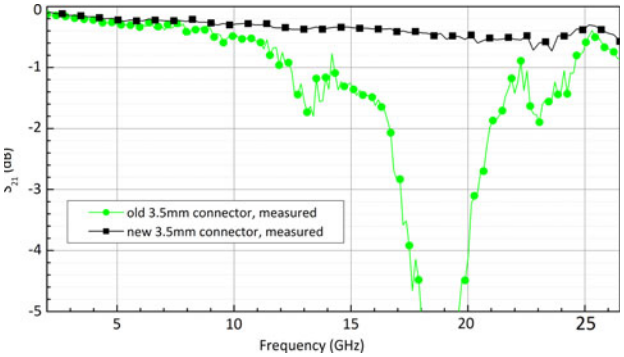


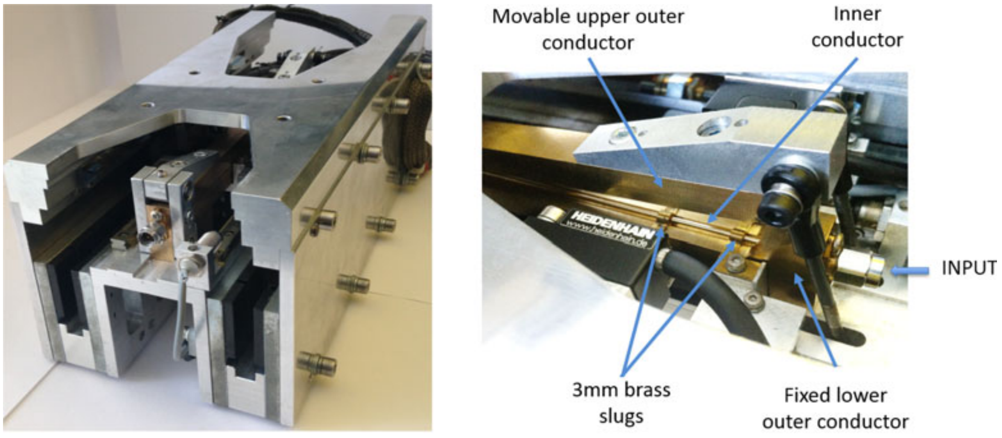
Fig. 10. Comparison of the tuner S_{21} parameters with the old and new 3.5 mm connectors (slugs are removed).

IV. EXPERIMENTAL RESULTS

The tuner characterization has been achieved using a four-port N5242AS PNA-X vector network analyzer (VNA) from Keysight Technologies. A high-performance coaxial cable has been used to connect the tuner to the VNA. A short open load thru calibration was performed to define the reference plane at the tuner input. A dedicated software has been developed to drive the impedance tuner together with the VNA. It allows the tuner calibration, the impedance synthesis, and some other options.

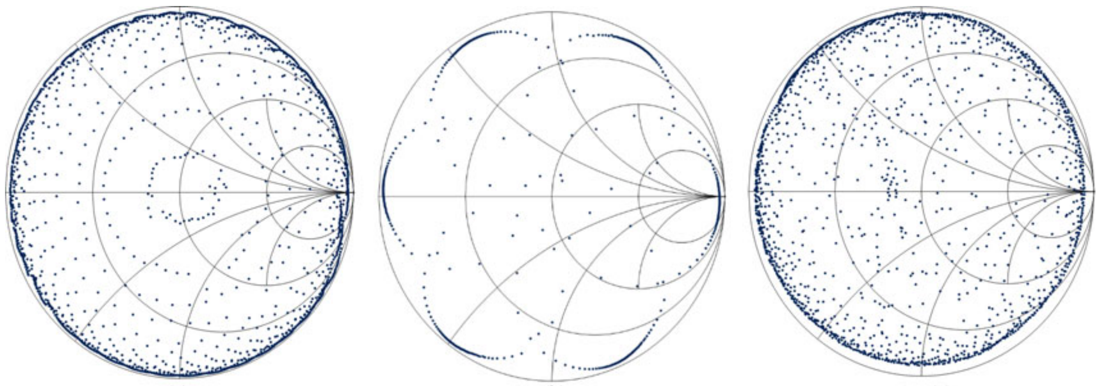
Figure 11 shows Smith chart examples of synthesized impedances at 4, 9, and 12 GHz using the 3, 7, and 14 mm long slugs, respectively. Figure 11(a) and 11(b) illustrates the impedance synthesis using the second and first principles introduced in previous sections. Figure 11(c) shows a Smith chart with much more impedances achieved using the second impedance synthesis principle. It can be observed that the tuner can achieve any impedance and reach very high VSWR values located at the Smith chart edge.

In Fig. 12, the minimum and maximum values of the maximum VSWR achieved around the Smith chart periphery (for all reflection coefficient angles on the Smith chart) versus frequency in simulation using ADS schematic for 3 and 7 mm long slugs are compared to the measured maximum VSWR. It can be seen that measured results are quite in a good



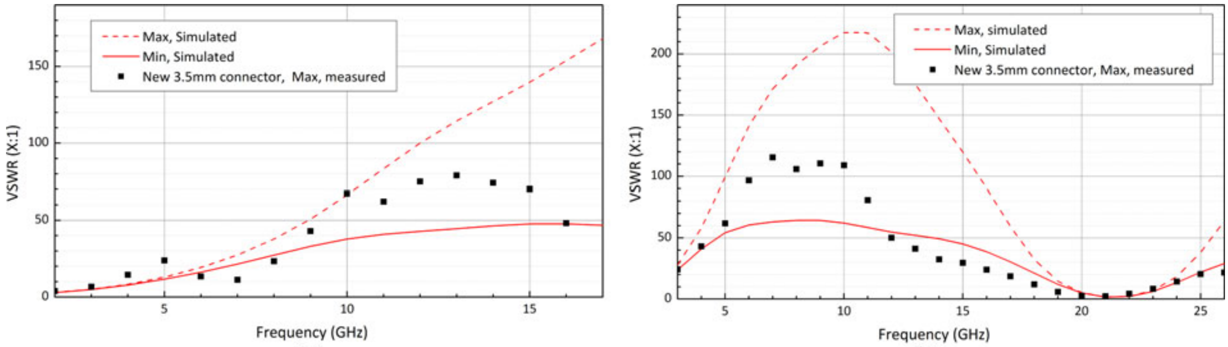
(a) (b)

Fig. 9. (a) Overall view of the fabricated prototype and (b) detailed view in opened position.



(a) (b) (c)

Fig. 11. Measured synthesized impedances at (a) 4 GHz with 14 mm long slugs using the second principle, (b) 9 GHz with 7 mm long slugs using the first principle, and (c) 12 GHz with 3 mm long slugs using the first principle.



(a) (b)

Fig. 12. Measured and simulated VSWR versus frequency for (a) 3 mm and (b) 7 mm long slugs.

agreement with the simulated results. Investigations are ongoing to explain the discrepancy between simulated and measured results to improve both the model accuracy and the prototype performances. The axiality of the main coaxial line inner conductor could be a first issue. Also, additional surface roughness loss due to a poor milling surface finishing of the main coaxial line outer conductor achieved using a ball end milling cutter could be the reason of the disagreement at high frequencies. Additional loss explains that the maximum measured VSWR is below the ADS schematic model minimum VSWR in Fig. 12(b).

V. CONCLUSION

This paper presented theoretical, simulated, and experimental results related to the development of a novel type of programmable impedance tuner offering high VSWR. This tuner is based on two independent reflective coaxial slugs having low characteristic impedance and sliding with high repeatability [10] along a 50 Ω coaxial line. Depending on the targeted frequency band, different slugs can be used to obtain an optimal VSWR. A prototype has been fabricated with a set of three pairs of slugs to demonstrate the interest of the proposed approach for impedance synthesis. This prototype, based on brass, can be optimized. It has been demonstrated in theory and simulation that silver plating the tuner coaxial elements, a significant improvement in term of VSWR and transmission loss can be achieved. Additionally, the minimal distance between the input connector and first slug can be reduced by a mechanical redesign of the prototyped tuner, to provide even higher VSWR. The IMS Research Center and Advtech are now looking for partners to develop and push forward this promising technology.

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