On the Tuning Range of a Reconfigurable Half-Mode Substrate-Integrated Cavity Antenna

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***Abstract*—In this paper the theoretical maximum tuning range of a frequency-reconfigurable antenna based on a half-mode substrate-integrated cavity is investigated and discussed. The antenna, which has recently been proposed by the authors, demonstrated a measured frequency tuning range of about 42% based on the capacitance range offered by practically available varactors. In the present investigation, the capacitance range is assumed to be unlimited, i.e. varying from 0 to infinity; then the tuning range is analytically calculated for different structure dimensions. It is shown that theoretical upper limit for the tuning range of this antenna is about 80% when the loading stubs' length is equal to the half guided-wavelength at the maximum frequency of operation. This investigation provides guidelines on the stub sized to be used in the design of stub-loaded reconfigurable antennas to achieve a maximum continuous tuning range.**

***Index Terms*—Half-Mode Substrate-Integrated Waveguide (HMSIW), waveguide cavity, reconfigurable antennas, periodic structures, tuning range.**

I. INTRODUCTION

With the emergence of smart wireless systems, reconfigurable antennas are becoming increasingly attractive to the research and industry communities [1], [2]. In parallel, substrate-integrated waveguide (SIW) technology, which was proposed in the late 1990s [3], has provided an effective pathway to design antennas and other microwave components due to many advantages such as low-loss, low-cost and ease of circuit integration. In particular, the Half-Mode Substrate-Integrated Waveguide (HMSIW), which has its lateral size almost reduced by half compared to the SIW [4] demonstrated as attractive platform for the design of antennas due to the intrinsic presence of an aperture [5]–[10].

Recently, a frequency-reconfigurable antenna based on a stub-loaded HMSIW cavity has been proposed with a thorough analytical model for the prediction of its resonance frequency and detailed optimization procedure for the tuning range [11]. For the design of this reconfigurable antenna, the tuning range has been optimized targeting a specified bandwidth, i.e. S-band, for a given substrate and capacitance range of varactors. This design has been fabricated and the measured results demonstrated a tuning range of 42% with a total accessible bandwidth of 44% [11]. However, the tuning range of this antenna may be increased if varactors with wider capacitance range are used. These devices may become available as the varactor technology evolves. Thus, this paper will investigate the upper theoretical limit for the tuning range of this reconfigurable antenna, i.e. for an unlimited range of varactor capacitance, extending from 0 F to infinity. Besides providing a theoretical limit on the frequency tuning range of this antenna, this investigation also gives a better insight into the operation principle of this periodically loaded cavity, where bandgaps appear in the dispersion diagram [12]. The study also helps further understanding the operation mechanism of a polarization- and frequency-reconfigurable microstrip patch antenna [13], in which a similar technique of employing periodically loaded stubs was utilized.

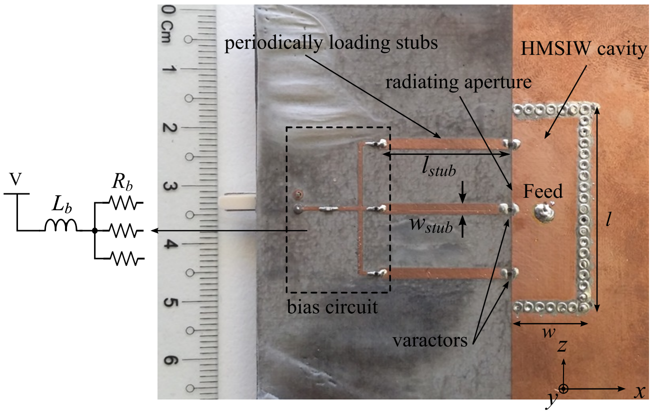


Fig. 1. Photograph and design of a reconfigurable antenna based on a stub-loaded HMSIW cavity [11]. The back side of the substrate is a full ground plane. The bias circuit consists of large resistors (R_b) to realize RF open-circuit at the end of the stubs, followed by a choke inductor (L_b).

The paper will start by revising the design and operation principle of the considered antenna, as well as briefly explaining the theoretical analysis for the resonance frequency of the structure. Then the tuning range will be investigated for different structure dimensions assuming an unlimited capacitance range. Further explanations and discussions will be provided on that basis, followed by a conclusion about the maximum achievable tuning range and design rules for the optimization of this type of stub-loaded reconfigurable antenna.

II. ANTENNA DESIGN AND OPERATION PRINCIPLE

The design of the antenna and bias network are described in detail in [11]. The main antenna features will be briefly revised in this section for the reader's convenience. The antenna consists of a HMSIW cavity, which on resonance radiates from its open aperture as a magnetic dipole on a ground plane. The cavity aperture is loaded with three stubs located periodically along z-direction as shown Fig. 1. The varactors bridge the stubs with the HMSIW cavity aperture. The bias network is designed to ensure an RF open-circuit at the end of the stub as well as provide reverse DC bias voltage for the three varactors [11].

When the varactor capacitance is tuned by changing the reverse bias voltage $C = C(V)$, the impedance loaded at the open aperture is varied and therefore the wavenumber in x-direction k_x is changing [12]. Since the resonance frequency f_r for a rectangular cavity is calculated as

$$f_r = \frac{c_o}{2\pi\sqrt{\epsilon_r}}\sqrt{k_x^2 + k_y^2 + k_z^2}, \qquad (1)$$

the resonance frequency of the antenna will also change. Here ϵ_r is the relative permittivity of the substrate and k_x, k_y, k_z are the wavenumbers in x, y, z-direction respectively. By applying the transmission line model on the loading stubs, they can be shown to provide an additional capability for impedance manipulation in the optimization of this antenna. The resonance frequency of the antenna is calculated using equation (1) where $k_y = 0$ due to the thin substrate and $k_z = \pi/l$ due to the two short-circuit walls in z-direction. The wavenumber in x-direction k_x can be obtained from [12] with an adjustment as an accuracy improvement proposed in [11]. For a given available varactor capacitance range, the antenna and stub dimensions $(w, l, w_{stub}, l_{stub})$ (Fig. 1) are optimized targeting a specified frequency tuning range. The detailed optimization can be found in [11]. In this paper, the tuning range will be calculated and discussed for the case of unlimited varactor capacitance range $C \in [0, \infty)$ F. The results will be shown in the next section.

III. ANTENNA TUNING RANGE

The selected material is copper-clad Rogers Duroid 5880 with relative permittivity $\epsilon_r = 2.2$ and thickness $h = 1.524$ mm. Via hole spacing and diameter are chosen as $s = 1.85$ mm and $d = 1.05$ mm. Figure 2 shows the resonance frequency as a function of varactor capacitance C for different values of stub length l_{stub} for a particular HMSIW cavity dimension: $l = 37$ mm, $w = 13.875$ mm. The stub width has been shown in [11] to only have a minor impact on the tuning range compared to l_{stub}, and thus a fixed value of $w_{stub} = 2$ mm is chosen. Figure 3 plots the upper and lower limits of the tuning range as l_{stub} increases from 0 mm to 40 mm.

It can be observed that the lower limit of tuning range keeps decreasing when l_{stub} increases (the resonance frequency reaches its lower limit when $C \to \infty$). This is as expected because when $C = \infty$, the varactors act as short-circuits and the structure (including the stubs) becomes electrically larger as l_{stub} increases. On the other hand, if only considering $l_{stub} < 25$ mm, the upper limit of frequency range remains constant. This is also as expected because when $C = 0$, the varactors act as open circuits and the antenna resonates at the resonance frequency of the HMSIW cavity without any stub.

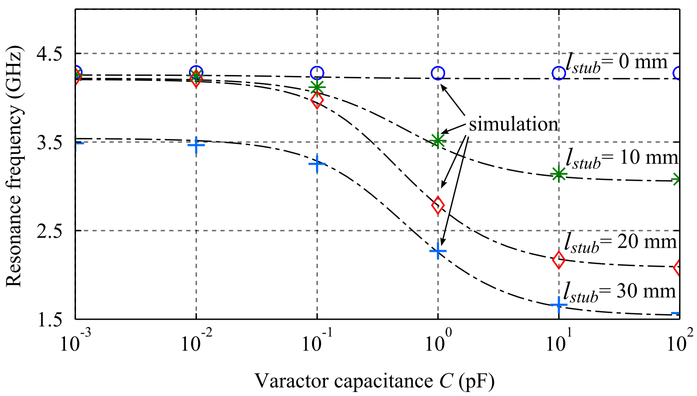


Fig. 2. Resonance frequency at different capacitance values. Continuous curves are analytical results while discrete points are simulation results.

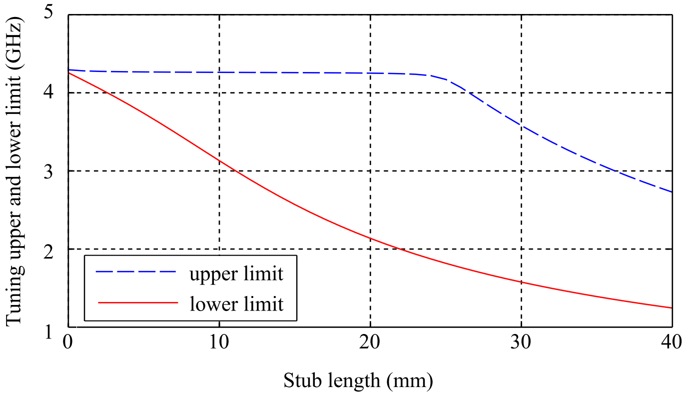


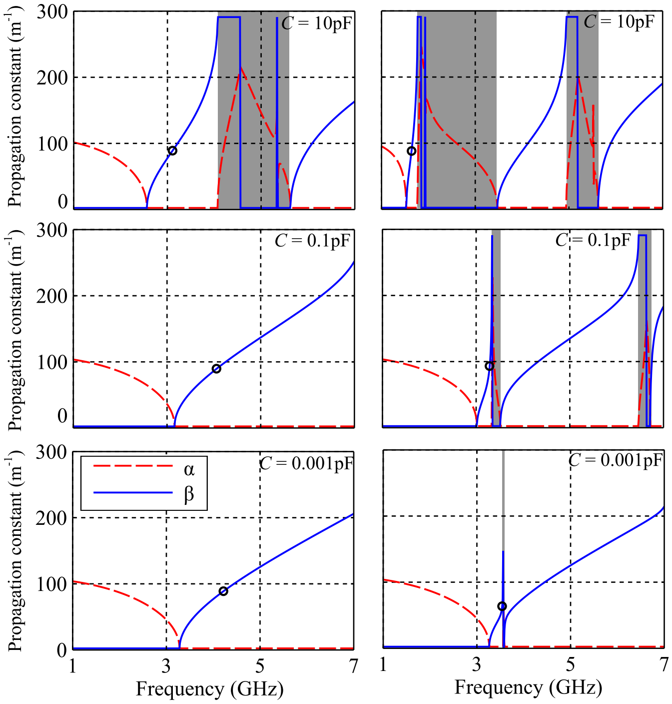
Fig. 3. Upper and lower limits of the tuning range for different values of stub length l_{stub}.

This upper limit frequency range can be simply estimated as

$$f_r^{max} \approx \frac{c_o}{2\sqrt{\epsilon_r}}\sqrt{\left(\frac{1}{2w_e}\right)^2 + \left(\frac{1}{l}\right)^2}, \qquad (2)$$

with w_e being the effective width of the HMSIW [4]. This formula yields a frequency of 4.41 GHz, which agrees with the results shown in Figs. 2 and 3 showing a corresponding value of 4.27 GHz. The minor discrepancy between these two values is due to the parasitic capacitance between the stubs and the antenna aperture. Nevertheless, this suggests that the tuning range should increase when the stub length gets larger. Unfortunately, this increase is only observed up to $l_{stub} = 25$ mm. Beyond this value, the upper frequency limit of the tuning range starts decreasing, which seems to contradict the above explanation.

The apparent problem of decreasing the upper limit of the tuning range for increasing l_{stub} beyond a certain length can be better understood if the propagation constant of the periodically loaded traveling-wave HMSIW [12] is examined. As demonstrated in [12] and generally expected for periodic structures, the Floquet mode analysis reveals bandgaps in the dispersion curves for this type of waveguide. Fig. 4 shows the calculated propagation constant $\gamma = \alpha + j\beta$ of a periodically stub-varactor-loaded HMSIW at different values of varactor



(a) l_{stub} = 10 mm (b) l_{stub} = 30 mm

Fig. 4. Propagation constant ($\gamma = \alpha + j\beta$) of the periodically loaded traveling-wave HMSIW with the same width ($w = 13.875$ mm) as the cavity. The left and right columns are plotted for $l_{stub} = 10$ and 30 mm respectively. The black dot shows the position of resonance of the cavity considered in Fig. 2-3, i.e. for a cavity length $l = 37$ mm. The shaded areas are the bandgaps in this periodic structures.

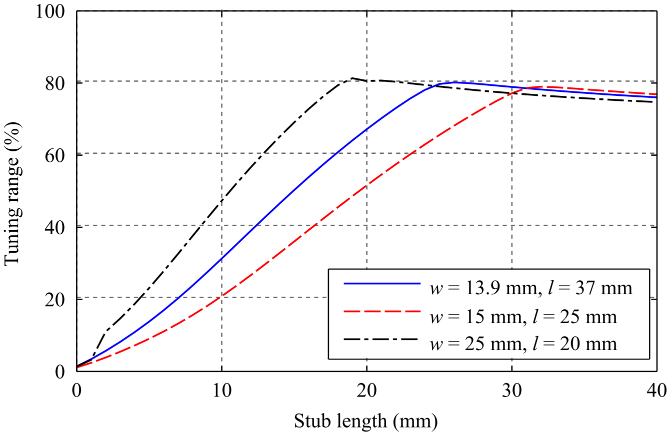


Fig. 5. Maximum tuning range as a function of stub length for different HMSIW cavity dimensions.

capacitance C and stub length l_{stub} [12]. It can be verified from these figures that, as $C \to 0$, the periodically loaded HMSIW approaches the conventional HMSIW, i.e. without reactance loaded. However, in the case $l_{stub} = 30$ mm, due to the larger stub length, a bandgap is observed as $C \to 0$ and causes the upper limit of the tuning range to decrease. It is noted that the tuning upper limit, i.e. the black dot in the bottom right figure, is the frequency at which the stub length equals to half guided-wavelength. Furthermore, the results for $l_{stub} = 30$ mm suggest that there will be another resonance for frequency range greater than about 3.5 GHz. This resonance will be the same as f_r^{max} (defined in equation (2)) when $C \to 0$, which is expected as discussed previously.

Finally, the maximum achievable relative tuning range, defined as $2(f_{max} - f_{min})/(f_{max} + f_{min})$, can be calculated for different values of stub lengths. Here f_{max} and f_{min} are the resonance frequencies corresponding to $C = 0, \infty$ F respectively (shown in Fig. 3). It can be observed from Fig. 5 that for various selected HMSIW cavity dimensions, the maximum tuning range remains approximately about 80%. Further calculations show that this happens consistently when $l_{stub} \approx \lambda^{min}/2$ where

$$\lambda^{min} = \frac{c_0}{\sqrt{\epsilon_{eff}} f_r^{max}} \tag{3}$$

and ϵ_{eff} is the effective permittivity of the microstrip line modeling the loading stub.

In practice, the tuning range of a varactor is limited by the current technology, thus an optimization as demonstrated in [11] is utilized to maximize the range within these constraints. The results from the above investigation indicates however that the stub length should not be chosen greater than half guided-wavelength at the upper limit frequency because when $l_{stub} > \lambda^{min}/2$, there is no further possible gain in tuning range (Fig. 5). This can be expected by applying transmission line theory on the stubs (or simply using a Smith chart): a long stub is equivalent to the one that is a half guided-wavelength shorter. In other words, the stub length should be selected such that no bandgap appears in the targeted tuning range. This can easily be verified by calculating the propagation constant γ of the corresponding periodically loaded traveling-wave HMSIW. Once the limit on stub size is determined, the optimization process can be carried out as described in [11].

IV. CONCLUSION

In this paper, the theoretical limit for the frequency tuning range of a reconfigurable antenna based on HMSIW cavity has been discussed. The results from our semi-analytical considerations bring a further understanding on the antenna operational mechanism when varying the varactor capacitance in the whole possible range, i.e. $[0, \infty)$ F. The maximum possible continuous tuning range for this type of antenna is shown to be approximately 80% for various structure dimensions. The result also justifies the range of the stub dimensions for the antenna optimization process which was proposed in [11].

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