An Independently Reconfigurable Upper and Lower Band Edge of Yagi Uda Antenna

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Abstract—In this letter, a novel design of independently reconfigurable upper and lower bands of a Yagi-Uda antenna is presented. The reconfiguration approach used in this antenna is based on keeping either the upper or lower band edge fixed with gradually increasing the bandwidth to the lower or upper ones. In this system, PIN diodes are used to control the length of the resonator and the slot-line of Yagi-Uda antenna to achieve upper and lower bandwidths limit reconfigurability. An antenna prototype was fabricated and tested in order to validate the design approach of the bandwidth reconfiguration. The proposed antenna has several different modes of operation with capability of tuning the fractional bandwidth (FBW) from 7% to 33% and 18% to 72% when using resonator and slot-line, respectively. This antenna can be a good candidate for cognitive radio applications that need adjusting the frequency bandwidth.

1. INTRODUCTION

Recently, with the advances in various wireless communication systems, the demand on using free space to send and receive data is increasing; however, the saturation of the spectrum capacity has become a concern [1–5]. Therefore, developing systems that operate at different frequencies with the ability to switch on the unoccupied frequency bands can solve the problem, with the condition to maintain the same communication quality [6, 7]. Frequency reconfigurable antenna is considered as a key element in modern wireless multiband and wideband communication systems because it allows the reduction of space, cost, and complexity [4, 5]. In the literature, three categories of reconfigurable microwave component can be noticed: reconfigurable antenna in terms of bandwidth [3], reconfigurable antenna in terms of centre frequency [5], and reconfigurable Power Divider in terms of bandwidth and centre frequency [6]. However, bandwidth reconfiguration design with fixed edges has been barely reported in the literature [7]. In this context, a disc-monopole antenna with four vertical slot lines and a via-shorted slot ring is proposed in [8]. This antenna has several reconfigurable modes of bandwidth with a fixed lower band limit and a variable upper one. In [6], a Dual-Band Bandpass Filter based on Terminated Cross-Shaped Resonators (TCSR) was proposed to achieve reconfigurable bandwidths with lower limit.

In this letter, a Yagi-Uda bandwidth reconfigurable antenna with a fixed lower or upper band edge is proposed. It is worth mentioning that to date, no reconfigurable antenna with a fixed lower or upper band edge reported in literature exhibits reconfigurable bandwidth. The reconfiguration mechanism is accomplished by using PIN diodes in order to control the electrical lengths of the microstrip resonator located in the back side of the antenna as well as the lengths of slot-lines. The proposed Yagi-Uda antenna provides several tuning states with wider FBW tuning range.

2. PROPOSED ANTENNA STRUCTURES

The layout of the proposed antenna is illustrated in Fig. 1. This antenna has already been reported in [2]. The antenna is built on a $36\,\text{mm} \times 44\,\text{mm}$ Rogers RO 4003 substrate with a dielectric constant ε_r of 3.38 and a thickness of 0.5 mm. The antenna is composed of a circular stub microstrip placed on the bottom side of the substrate and a feeding microstrip line with a characteristic impedance of $50\,\Omega$. The driver dipole, parasitic strip element, and slot-line with circular stub are printed on the top substrate layer. The main radiation element is one of the parallel dipoles, and the remainders of the radiation's elements are the printed strips director and the microstrip-to-slot-line transition as feed.
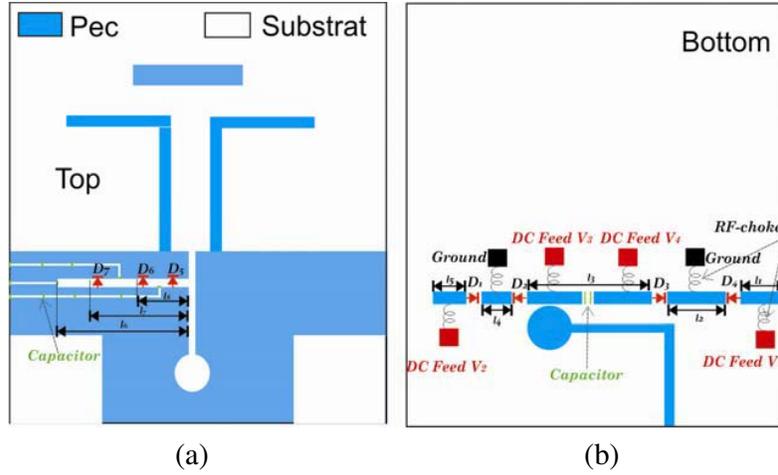
Figure 1. Configuration of the proposed antenna: (a) Top layer, (b) bottom layer.

To enable the operation of the antenna in different modes, one slot-line containing three PIN diodes (Figure 1(a)) and one transmission line resonator containing four PIN diodes were used (Figure 1(b)). The resonator has a filtering effect in which it rejects frequencies around $\lambda/4$ by considering the length of the resonator. It is important to notice that the horizontal position of the transmission line resonator does have an effect on the resonance frequency of the bandwidth. The transmission line resonator is illustrated in Figure 1(b). The switching of the stub resonator between different biasing voltages is allowed by the insertion of the four PIN diodes in the microstrip line. During the application of biasing voltage of $(+5\,\text{V})$, the transmission line stub resonator R_1 can be connected to the other resonator, which results in a new configuration that operates as a band-stop filter due to the quarter wave $(\lambda/4)$ line of the open stub resonator. Simultaneously, the PIN diodes would turn OFF by the application of a negative voltage $(-5\,\text{V})$ which disconnects transmission line. Therefore, the transmission line stub resonator acted as an all pass wide band. The lumped elements (capacitor) were used to isolate the positive and negative voltages. The order of the four diodes is accomplished using four voltage sources.

The behaviour of the proposed reconfigurable antenna is analysed using the $ABCD$ matrix which is expressed as follows [4]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos \beta l & jZ_t \sin \beta l \\ jY_t \sin \beta l & \cos \beta l \end{bmatrix} \tag{1}$$

where Z_t and Y_t are the characteristic impedance and admittance of the transmission line. The same formula can be applied in our approach

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_{L1} M_{L2} M_{L3} M_{L4} M_{L5} \tag{2}$$

where $ABCD$ matrix of the resonator

$$= \begin{bmatrix} 1 & 0 \\ \dfrac{j \cot \theta_{L1}}{Z_t} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j \cot \theta_{L2}}{Z_t} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j \cot \theta_{L3}}{Z_t} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j \cot \theta_{L4}}{Z_t} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{j \cot \theta_{L5}}{Z_t} & 1 \end{bmatrix}$$

When $\theta = \frac{\pi}{2}$

$$S_{21} = \frac{2}{A + B + C + D} = \frac{2jZ \cot(\theta_{L1} + \theta_{L2} + \theta_{L3} + \theta_{L4} + \theta_{L5})}{Z_t^2} \tag{3}$$

When $S_{21} = 0$ (notched band), the transmission zero can be expressed as:

$$f_z = \frac{2f_0}{\pi} \tan^{-1}(\cos\theta_{L1} + \theta_{L2} + \theta_{L3} + \theta_{L4} + \theta_{L5}) \tag{4}$$

From this formula, it can be concluded that the transmission zero frequency (f_z) can be controlled by the electrical length of the resonator ($\lambda_{L1}/4 + \lambda_{L2}/4 + \lambda_{L3}/4 + \lambda_{L1}/4 + \lambda_{L1}/4$) and the state of the diode.

3. FABRICATION, EXPERIMENTAL RESULTS AND DISCUSSION

The different switch configurations corresponding to the different modes are given in Table 1.

Table 1. Switch configurations for the different modes.

Techniques	Resonator				Slot-line		
	D_1	D_2	D_3	D_4	D_5	D_6	D_7
Mode 1	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Mode 2	OFF	**ON**	OFF	OFF	OFF	OFF	OFF
Mode 3	**ON**	**ON**	OFF	OFF	OFF	OFF	OFF
Mode 4	**ON**	**ON**	**ON**	OFF	OFF	OFF	OFF
Mode 5	**ON**	**ON**	**ON**	**ON**	OFF	OFF	OFF
Mode 6	OFF	OFF	OFF	OFF	**ON**	OFF	OFF
Mode 7	OFF	OFF	OFF	OFF	**ON**	**ON**	OFF
Mode 8	OFF	OFF	OFF	OFF	**ON**	**ON**	**ON**

The different modes are obtained by controlling the resonator and slot line. Therefore, modes 1 to 5 are the results of controlling the diodes of the resonator (D1, D2, D3, and D4) while the diodes of the slot-line (D5, D6, and D7) are OFF, and modes 6 to 8 are the results of controlling the slot-line diodes while the resonator diodes are OFF [9].

Table 1 summarizes the corresponding PIN diode states for antenna operation in the eight different modes.

Table 2 summarizes the frequency bandwidth and fixed frequency lower and upper for antenna operation for different modes.

Table 2. Upper and lower band edge for the different modes.

Techniques	Upper band Edge	Lower band Edge
Resonator	**Fixed** at 7 GHz	5–6.5 GHz
Slot-line	5.1–8.9 GHz	**Fixed** at 4.2 GHz

Figure 2 shows a prototype of the proposed reconfigurable antenna. The simulated and measured return losses S_{11} of the designed antenna with different modes, which are plotted using CST MWS and Vector Network Analyser (8719ES), are presented in Figure 3.

The measured and simulated return losses of the bandwidth reconfigurable antenna are shown in Figure 3. Resonator techniques enable the realization of five different bandwidths with fixed upper
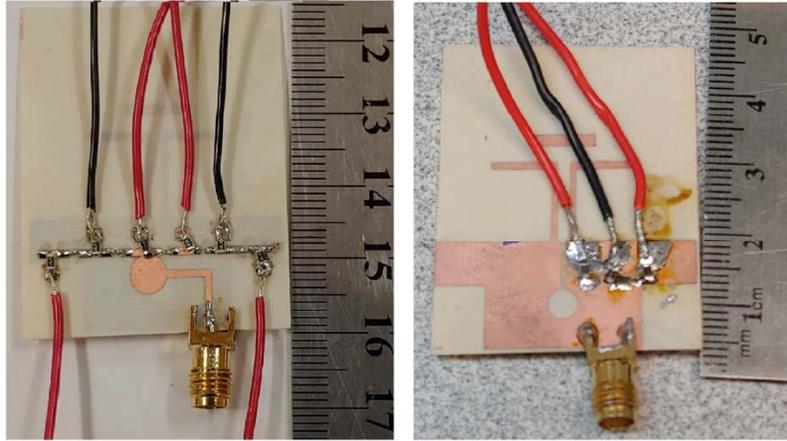
Figure 2. Photos of the fabricated antenna and transmission line resonator.
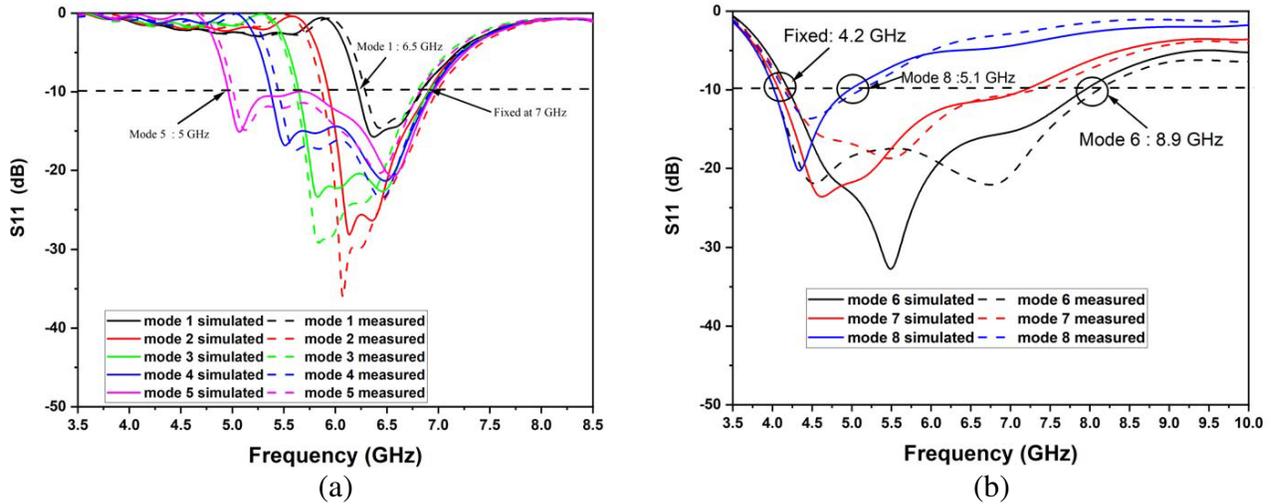
Figure 3. Measured and simulated performance of antenna: (a) Resonator technique, (b) slot-line technique.

edge, and the slot line techniques enable the realization of three bandwidths with fixed lower edge. The range of the resonance frequency of mode one and mode five are 6.5–7 GHz and 5–7 GHz, respectively.

Therefore, the proposed antenna has the ability to tune the lower edge bandwidth from 5 to 6.55 GHz by keeping the upper edge fixed at 7 GHz. Similarly, the range of the resonance frequency of mode six and mode eight are 4.2–8.9 GHz and 4.2–5.1 GHz, respectively.

Thus, the proposed antenna has the ability to tune the upper edge bandwidth from 5.1 to 8.9 GHz by keeping the lower edge fixed at 4.2 GHz. The measurement results are almost in good agreement with the simulation ones.

$$\text{FBW} = 2\left(\frac{f_2 - f_1}{f_2 + f_1}\right) \tag{5}$$

The FBW can be calculated from formula (5), where f_1 is the lower frequency, and f_2 is the upper frequency. The following Table 3 summarizes the FBW of all modes.

Consequently, the resonator technique made possible the design of a reconfigurable antenna which gradually varies its bandwidth from 7% to 33% (Table 3) by keeping the lower band edge fixed and varying the upper cut-off frequency in five different modes as shown in Figure 3(a).

Table 3. Fractional bandwidth (FBW) for the different modes.

Technique used	$f_{1(\text{mode 1})}$	$f_{2(\text{mode 1})}$	FBW%	$f_{1(\text{mode 5})}$	$f_{2(\text{mode 5})}$	FBW%
resonator	6.5 GHz	7 GHz	7%	5 GHz	7 GHz	33%
Technique used	$f_{1(\text{mode 8})}$	$f_{2(\text{mode 8})}$	FBW%	$f_{1(\text{mode 6})}$	$f_{2(\text{mode 6})}$	FBW%
Slot-line	4.2 GHz	5.1 GHz	18%	4.2 GHz	8.9 GHz	72%
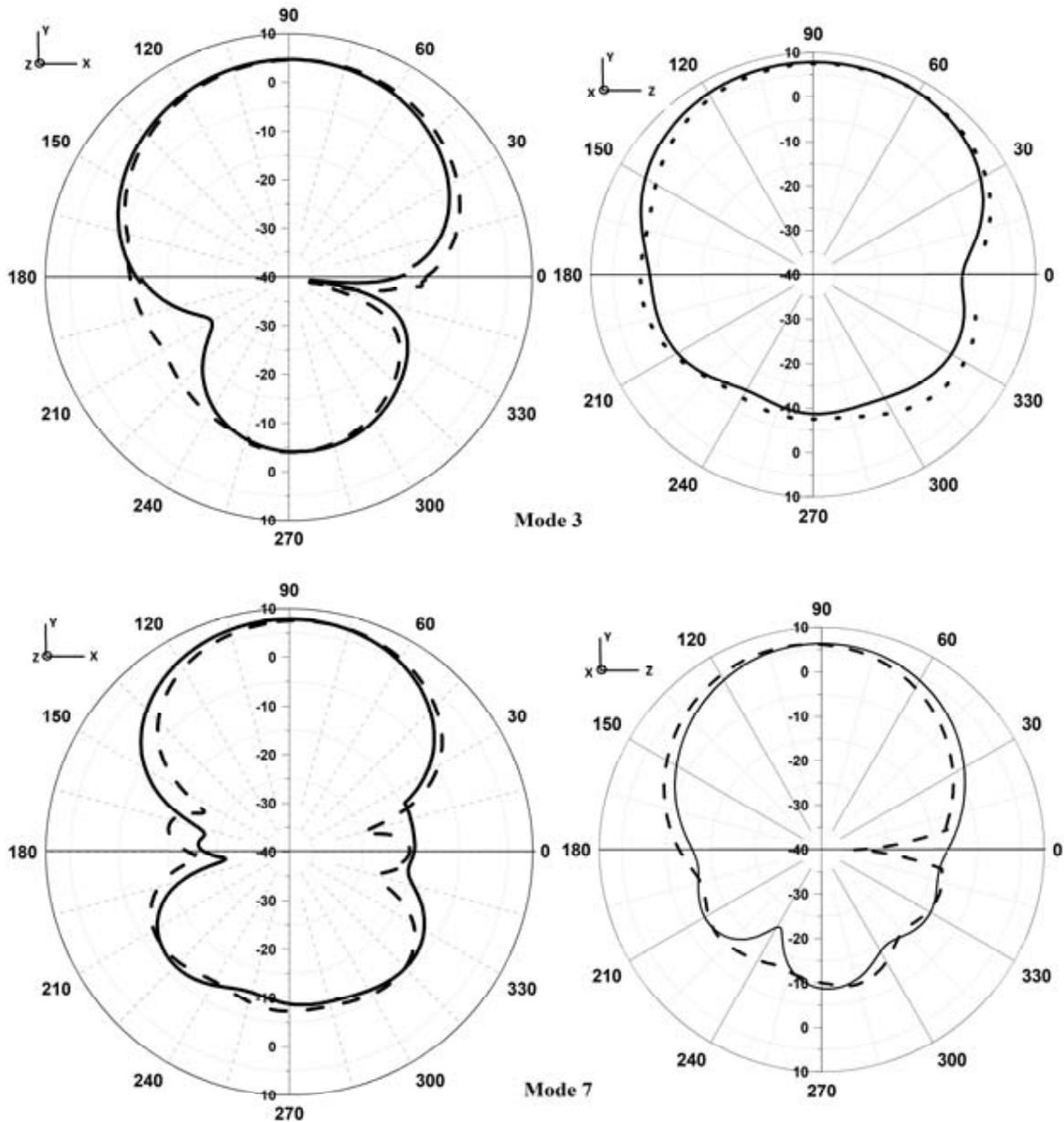
Figure 4. Measured and simulated radiation patterns in mode 3 and mode 7 at 6.5 GHz and 5 GHz respectively.

On the other hand, slot-line techniques make possible the design of reconfigurable antenna that can gradually vary its bandwidth from 18% to 72% (Table 3) by keeping the upper band edge fixed and varying the lower cut-off frequency in three different modes as shown in Figure 3(b). The difference between the measured and simulated performances can be explained by the use of lumped components such as diode and resistor.

Figure 4 shows the measured and simulated antenna radiation patterns in XY and YZ planes at the centre frequencies of mode three at 3.5 GHz and mode seven at 6.5 GHz. We chose these two modes because they are in the middle of the two different techniques (resonator and slot-line techniques). Mode 3 is in the middle of modes 1 to 5, and mode 7 is in the middle of modes 6 to 8. From the figures it can be seen that the radiation patterns observed at XY and YZ planes are unidirectional ones for the different modes.

4. CONCLUSION

A novel design of Independently Reconfigurable Upper and Lower Band Edges of Yagi Uda Antenna is presented. The resonator transmission line has been analysed and designed to be integrated into the reconfigurable antenna. The proposed approach allows operating this antenna on keeping either the upper or the lower band edge fixed with gradually increasing the bandwidth to the lower or the upper ones. To validate the design concept, a prototype was fabricated and tested. The measured and simulate performances are in good agreement. The proposed antenna is suitable for cognitive radio applications which require bandwidth adjustment.

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