IET Microwaves, Antennas & Propagation

Research Article

Wideband dual-polarised SAW spiral antenna for monopulse system

ISSN 1751-8725
Received on 19th July 2017
Revised 12th October 2017
Accepted on 5th November 2017
doi: 10.1049/iet-map.2017.0689
www.ietdl.org

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Abstract: This study proposes a new technique for generating dual polarisation in spiral antennas. The proposed antenna is achieved by creating stair discontinuities in spiral antenna arms, entitled stair arm width (SAW) spiral antenna. Commonly, the spiral antenna is activated in direction finding systems, especially in wideband monopulse systems. Capability of generating sum and difference beams over a wide bandwidth is another feature of the proposed antenna. Radiation characteristics and generated modes of a wideband dual polarised four-arm SAW antenna in comparison with the modulated arm width (MAW) and conventional spiral antennas are presented. The cross-polarisation gain of SAW antenna, compared to MAW antenna, is decreased in difference pattern, which improves the antenna circular polarisation purity. Moreover, the input impedance of the proposed antenna with high n_s is more stable than MAW antenna over a wide bandwidth due to gradual discontinuities. Finally, a prototype four-arm SAW spiral antenna is built and evaluated with an available beamformer for 5.8–10 GHz frequency bandwidth. Simulated and measured radiation characteristics proved dual circularly polarised and wideband properties of the antenna.

1 Introduction

Monopulse is one of the radio direction finding systems, used in tracking radars. Direction finding in this system is based on organising sum and difference beams. An antenna which can yield sum and difference patterns in a wide frequency bandwidth is a key-component part of the wideband monopulse direction finding system [1]. Due to the ambiguity in the detection of the incoming waves, having a capable antenna to receive orthogonal circular polarised signals over wide bandwidths is necessary. Moreover, the sensor should also be able to estimate the angle of arrival (AOA) of radio-frequency signals. The best method to achieve these specifications is to use a frequency independent antenna with a multi-arm capability such as spiral, sinuous and log periodic antennas.

Spiral antenna is well known for providing constant radiation specifications and impedance over a broad frequency range and multi-arms properties. The spiral antenna provides a circularly polarised beam, with the handedness of circular polarisation determined by the wrapping direction of the arms. Having a feed point for the spiral, both outside and inside the radiation region, is one of the ways used to generate spiral antenna with capability to receive orthogonal signals [2, 3]. This method reduces the bandwidth and needs extra feeding network for exciting the end of spiral arms. Providing separate left-hand circular polarisation (LHCP) antenna and right-hand circular polarisation (RHCP) antenna is another solution to achieve dual circular polarised spiral antennas [4, 5]. However, this method duplicates antenna components which in turn leads to additional costs and space requirements. The best suggestion to reduce these problems is modulated arm width (MAW) spiral antenna.

MAW is a spiral-based structure for realising dual circular polarisation. MAW antenna has been described in [6–8] by Ingerson. The arm width of spiral antenna is modulated to form a band stop that reflects currents to generate dual polarised antenna. Although the MAW antenna was invented in 1970, the details of its high-quality dual polarisation operation have only recently been addressed in [9]. The operation of MAW antenna in mode 2 encounters some difficulties since the cross-polarisation of the antenna is increased, significantly. The axial ratio of MAW is increased in difference mode, which is in turn adversely affected by circular polarisation purity in this mode.

Moreover, high variations and swing in input impedance of the MAW antenna. This event is adversely affected by impedance matching and return loss of the antenna.

This paper proposes a new structure based on a spiral antenna to realise a dual circular polarisation named stair arm widths (SAW) spiral antenna. Stair discontinuities in the arm widths of spiral antenna generate a circular beam in the counter wrapping direction of the spiral arms. SAW antenna retains frequency independence by feeding the antenna from the centre. SAW antenna measures AOA and produces dual circular polarisation simultaneously, similar to what happens in MAW antenna.

The proposed structure improves the operation of the MAW antenna by modifying the method of creating discontinuities.

The cross-polarisation gain of SAW antenna, compared to MAW antenna, is decreased in difference pattern, which improves the antenna circular polarisation purity.

The paper has been organised as follows. Section 2 briefly discusses the theory of operation for MAW and SAW antennas and peruses the geometry of SAW antenna then, recommends the effect of various parameters. Phase progression of different modes and excitation network for the antenna in the four-arm case are studied in Section 3. Simulated performance of a four-arm SAW antenna is investigated in Section 4. Moreover, spiral antennas for three cases, equiangular, MAW and SAW are compared. Section 5 presents detailed measured performance of the SAW spiral antenna and the amount of difference between simulated and measurement results are explored. Finally, conclusions are drawn in Section 6.

2 SAW antenna theory of operation

The equiangular spiral antenna is first discussed by Rumsey in 1957 [10]. Equiangular spiral has a geometry which is entirely defined by angles as

$$r = r_{\text{in}}\,\mathrm{e}^{a\varphi} = r_{\text{in}}\mathrm{EXP}^{(\phi/(2\pi))} \tag{1}$$

where r_{in} is the starting radius, a is the growth rate, EXP is the expansion factor, φ is the progressive growth angle and r is the radial distance from the centre.

Depending on the number of arms and phase progression of the excitation between the arms, different radiation modes can be

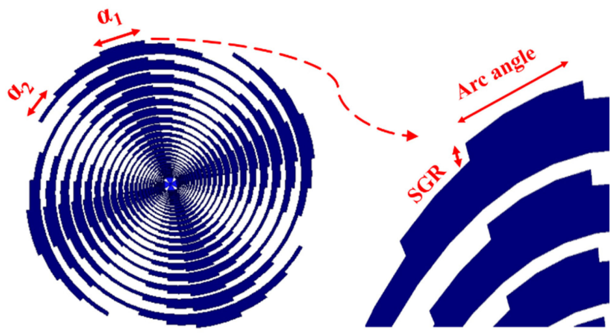


Fig. 1 *Geometry of non-identical stair SAW antenna (EXP = 1.5, m = 4, α1 = 18°, α2 = 12°, n_S = 7)*

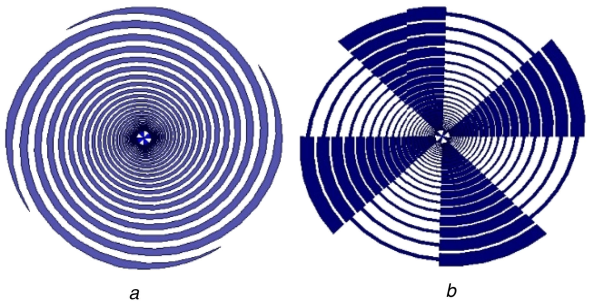


Fig. 2 *Four-arm spiral antenna structures*
(a) Logarithmic (EXP = 1.5), ***(b)*** MAW (EXP = 1.5, *m* = 4)

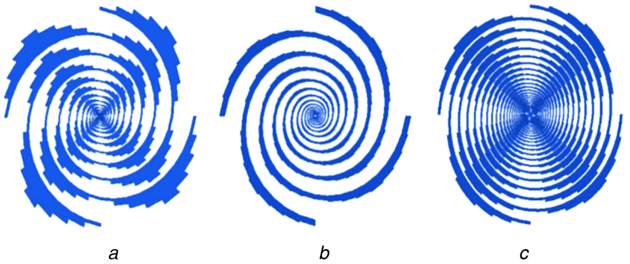


Fig. 3 *Four-arm identical stair SAW antenna with different EXP and m as*
(a) EXP = 3, *m* = 8, ***(b)*** EXP = 3, *m* = 2, ***(c)*** EXP = 1.5, *m* = 4

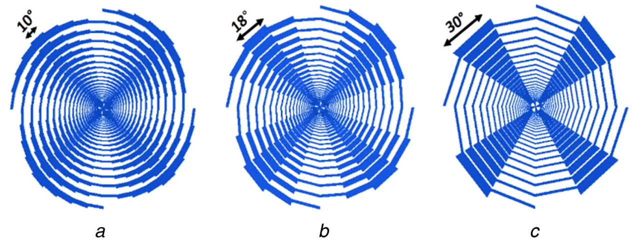


Fig. 4 *Four-arm identical stair SAW antenna with different n_S as (EXP = 1.5, m = 4)*
(a) n_S = 9, ***(b)*** n_S = 5, ***(c)*** n_S = 3

generated with unique input impedances and far-field pattern shapes for spiral antenna. The ratio of the sum and difference modes enables direct detection of AOA. The amplitude of this ratio determines the elevation angle and the resultant phase of the ratio specifies the azimuth angle [11].

A multi-arm spiral antenna, of N arms, can have N modes of operation. Radiation of the Mth mode occurs in the region, which is approximately $M\lambda$ in circumference, specifically where currents in adjacent arms are in phase, called active region. The active region moves closer towards the centre with increasing frequency and towards the perimeter of the antenna with decreasing frequency [11].

The turn on frequency of each mode is determined by

$$f_M = \frac{M * C}{2 * \pi * r_{\text{out}}} \tag{2}$$

where M is the mode number, c is the speed of light and r_{out} is the maximum radius of the spiral [12].

As stated before, this paper proposes a new found structure for producing a dual circular polarised spiral antenna named SAW (Fig. 1). Stair discontinuities produce gradual conversions in the arm width of spiral to generate SAW antenna. MAW spiral is another structure for realising dual polarised spiral antenna which has been addressed in the open literature. The arm width of spiral antenna is modulated between two high and low sections to form MAW antenna. To clarify this statement, logarithmic spiral and MAW geometries are shown in Fig. 2.

2.1 SAW spiral antenna parameters

Identical and non-identical stairs are two cases for creating discontinuities in the widths of spiral antenna arms to create SAW antenna. Expansion factor (EXP), modulation ratio (m) and number of stairs (n_s) are important parameters in designing identical SAW antenna. m parameter can be defined as the ratio of arm width in the highest and the lowest impedance sections. The lowest and the highest impedance sections of SAW antenna are on the stairs with the highest and the lowest arm widths. n_s is the number of stairs for each modulation cycle ($\lambda/4$ sections in four-arm SAW antenna). Fig. 3 illustrates three identical SAW antennas, geometries of which are varied by changing EXP and m parameters. The small amount of EXP and high amount of modulation ratio, *i.e. m,* improves the operation of the antenna in difference and reverse mode purity. Higher modulation ratio leads to increase impedance ripples, similar to what happens in MAW antenna [9]. Also, it provides more reflection current and better reverse mode ($m = -1$).

The arc angle of each stair and the ratio of any two stairs (SGR) in identical SAW structures are defined as

$$\text{arc} = \frac{\pi}{4 * n_s}, \quad (n_s = 1, 3, 5, 7, \ldots) \tag{3}$$

$$\text{SGR} = \frac{m}{(n_s - 1)/2 + 1} \tag{4}$$

Fig. 4 represents three identical SAW antennas with different n_S. Increasing n_s reduces the high variations and swing of input impedance. Parametric studies for n_s are provided in Section 4.2 of this paper. A new method for modulating spiral antenna is proposed in [13], which named taper arm width spiral. There is no published documentation that confirms the better performance of a taper spiral antenna. By the way, n_s of SAW should be increased in a way so that it does not lower the current reflection as much. In non-identical stair geometry, which has been presented in Fig. 1, the arc angle of each stair in a modulation cycle is different. The arc angle of central stairs is 18° while for the rest is 12°.

The number of modulation cycles around one spiral turn equals the number of arms. The stair discontinuities form the impedance discontinuities or reflection region (band stop), the same is true in MAW antenna. These band stops, keep the radiation region of the antenna inside the size necessary for forward mode operation and prevent radiation from higher difference patterns of a multi-arm spiral. According to Fig. 1, the basic spiral in the proposed antenna has an arm wound in the counter clockwise direction, which consequently detects RHCP. Reflecting the outwardly flowing currents in the reflection region causes the generation of opposite sense of circular polarisation, i.e. LHCP. This new mode is a reverse mode ($M = -1$).

Figs. 1 and 2*b* represent SAW and MAW antenna with the same modulation ratio. Discontinuities in the arm width of MAW antenna establish discontinuities in input impedance and generate the reverse mode by reflecting back the current. High variations and swing happen in the input impedance of the MAW antenna, due to abrupt and acute discontinuities in the arm width of MAW antenna. Gradual variation in SAW antenna encourages the

Table 1 Phase progression and modes of four-arm spiral, SAW and MAW antennas

Mode (*M*)	Arm 1	Arm 2	Arm 3	Arm4	Radiation pattern
1	0	90	180	270	sum (RHCP) spiral-SAW-MAW
3 and −1	0	270	180	90	diff (RHCP) spiral and sum (LHCP) SAW-MAW
2	0	180	0	180	diff (RHCP) spiral-SAW-MAW

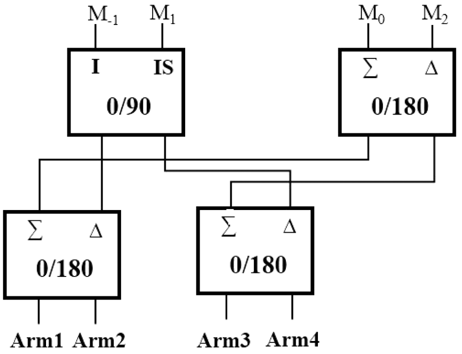


Fig. 5 *Schematic of a 4 × 4 butler matrix for excitation of the SAW antenna*

stability of antenna input impedance and removes high variation of input impedance.

3 Four-arm SAW antenna modes and excitation network

Generally, for the *N* arm spiral antenna, the phase excitation of *n*th arm in mode *M* is given by [14]

$$v_M^n = \mathrm{e}^{-\mathrm{j}2\pi M(n-1)/N} \tag{5}$$

Table 1 shows the generated mode in four-arm spiral, SAW and MAW antennas. The modulation ratio of MAW antenna is also defined as the ratio of arm width in high and low impedance section. Stair discontinuities in SAW antenna are clear, quite in contrast to abrupt discontinuities in the arm width of MAW antenna.

These excitations are provided by a 4 × 4 butler matrix shown in Fig. 5 [15]. As illustrated in this figure, it consists of three 180° and a 90° hybrid couplers. Butler matrices are used in a various beam-forming applications, including phased arrays and multimode antennas.

4 Simulation results

This section studies gain conversion versus frequency for equiangular, SAW and MAW spiral antenna. Input impedance of MAW and SAW has been compared as well.

4.1 Radiation properties

Figs. 6 and 7 investigate gain variations of antenna elements in Fig. 2 and SAW antenna shown in Fig. 4*b*, to survey frequency behaviour. The EXP is the same for all structures and the modulation ratio is the same for MAW and SAW antennas. All patterns are calculated at 30° theta angle since the maximum gain in difference mode occurs approximately towards 30° elevation angle. Figs. 6 and 7 are drawn average gain of 36 cuts ($\varphi = 0{:}360$ by 10° step).

All the elements have nearly constant gain over a wide frequency band. Spiral antenna outperforms others to produce a constant gain. Moreover, cross-polarisation of the spiral antenna is the lowest one (Figs. 7*a* and *b*). As expected, RHCP gain pattern is generated in the first mode for all geometries (Fig. 6*a*).

The second mode is difference beam with the handedness of RHCP polarisation. The difference mode of a four-arm MAW spiral and its application for direction finding have been addressed in [9] for the first time. Spiral antenna is the best choice to create pure circular polarisation with acceptable axial ratio. The looser-wrapped spiral requires a larger diameter to achieve the same low-frequency axial ratio. Loading the ends of the arms is a way to reduce the axial ratio. This way reduces the reflected mode radiation by the return loss of the loads relative to the spiral arm impedance. The efficiency decreases, but the axial ratio improves [16]. The operation of MAW and SAW in mode 2 encountered some difficulties since the circumferential location of the difference mode and reverse mode are the same and this degrades the circular polarisation purity of mode 2. The high cross-polarisation of the antenna in this mode and the similar phasing for both RHC and LHC polarisations at the feed has negative impact on mode 2 performance. The axial ratio and cross-polarisation are related as

$$\mathrm{AR[dB]} = 20\log\frac{10^{-(x/20)}+1}{10^{-(x/20)}-1} \tag{6}$$

where *x* is the cross-polarisation in dB. In most of the points, the cross-polarisation of SAW is lower at least 4 dB in comparison with MAW in difference mode, and the spiral antenna is the lowest (Fig. 7*b*). As a result, better circular polarisation of SAW antenna in difference mode is generated.

Fig. 7*c* is related to mode 3 in which the current reflection creates reverse mode in SAW and MAW antenna. Lower cross-polarisation in most of frequencies in SAW antenna, comparing to MAW antenna, is determined again (Fig. 6*c*).

4.2 Input impedance

The input impedance of the spiral antenna depends on the number of arms and the mode of operation. The arms input impedance of a self-complementary *N*-arm spiral in free space is derived from [17]

$$Z_{\mathrm{in}} = \frac{\eta}{4\cdot\sin(\pi\cdot M/N)} \tag{7}$$

where η is the intrinsic impedance of free space (377 Ω) and *N* is the number of structure arms. Consequently, the input impedance of self-complementary spiral antenna for sum mode ($M = \pm 1$) is 133.2 Ω and for difference mode ($M = 2$) is 88 Ω.

High input impedance of the self-complementary spiral antenna promotes employing impedance matching methods such as tapered baluns, marc hand baluns and so on. The simplest way for spirals with more than two arms is the direct feeding of each arm with a 50 Ω coaxial cable. Phase-matched cable feeds through the cavity and connects to a microwave circuit that generates modal excitations [16]. The beamformer provides a separate input port for each desired mode. The coax centre conductors feed the spiral arms.

The input impedances of MAW and SAW antennas with different n_s (7, 5 and 3) are simulated and shown in Fig. 8. According to this figure, high variations and jumping occur in MAW antenna input impedance. Higher n_s leads to reduce the variations and jumps of the resistance in the frequency bandwidth of the antenna. This figure demonstrates that the input impedances

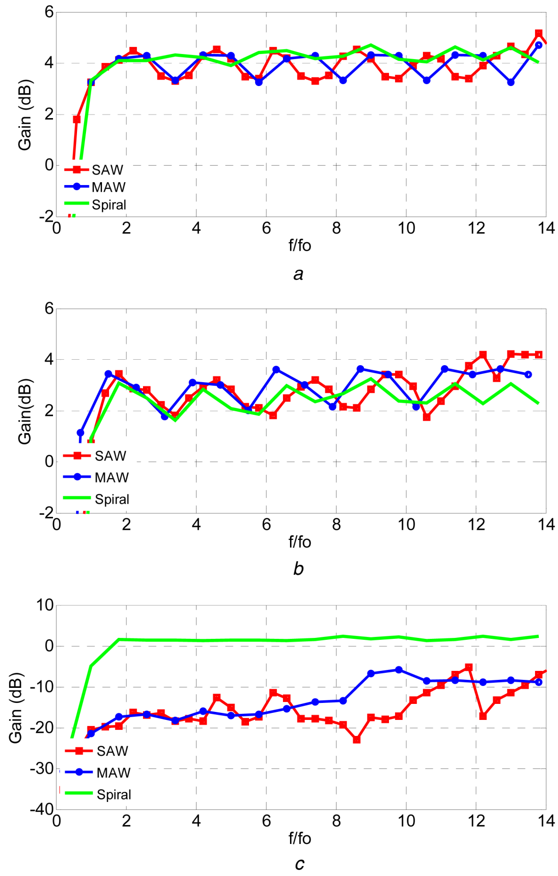


Fig. 6 *Comparison of spiral, SAW and MAW antennas for RHCP gain (φ = 0:360 by 10° step, θ = 30°)*

(a) *$M = 1$*, ***(b)*** *$M = 2$*, ***(c)*** *$M = 3$ and −1*

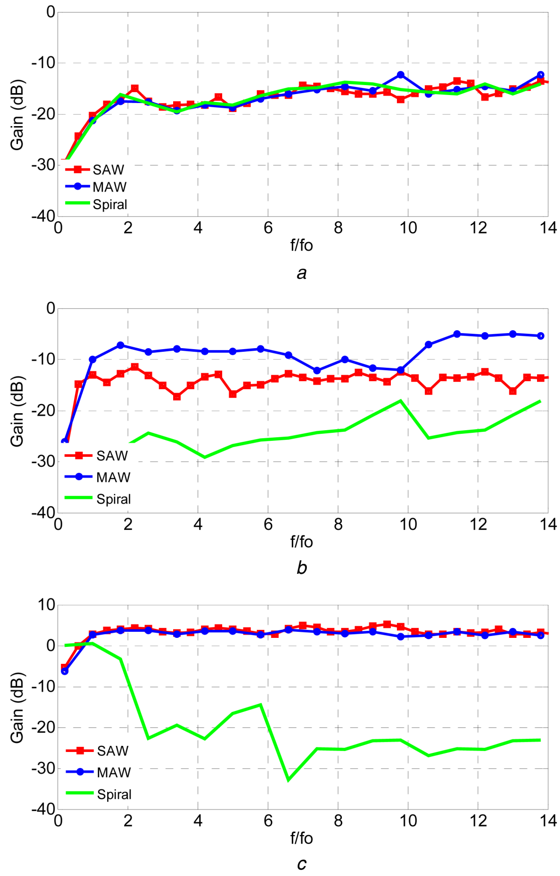


Fig. 7 *Comparison of spiral, SAW and MAW antennas for LHCP gain (φ = 0:360 by 10° step, θ = 30°)*

(a) *$M = 1$*, ***(b)*** *$M = 2$*, ***(c)*** *$M = 3$ and −1*

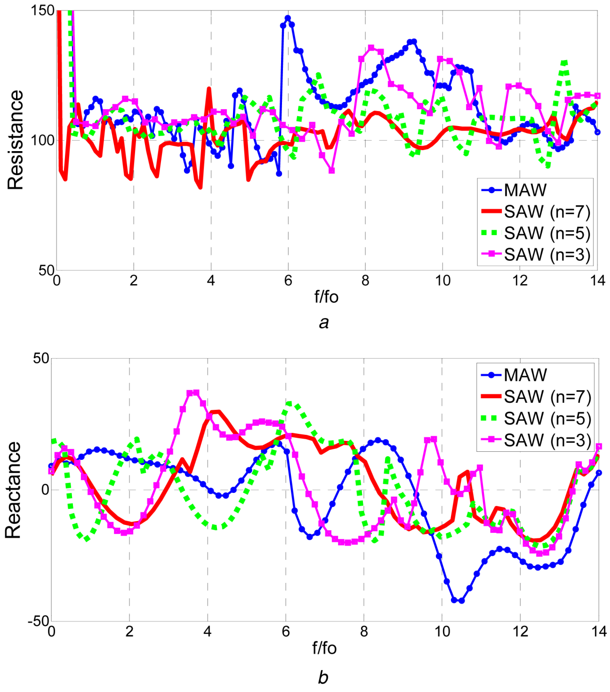


Fig. 8 *Input impedance of MAW and SAW antennas for different n_s*

(a) *Resistance*, ***(b)*** *Reactance*

of SAW and MAW antennas are similar, approximately, for small n_s. The imaginary part of the impedance is not as stable as its real part and it varies in larger band in comparison with the real part. Increasing n_s reduces the variations band in imaginary part of the antenna impedance.

5 Measurements

Finally, by considering a limitation of printing antenna, a prototype of the SAW antenna showing the best performance is constructed.

A photograph of the fabricated antenna is shown in Fig. 9. The antenna parameters are EXP = 1.5, $R_{out} = 7$ cm, $m = 4$, $n_s = 7$. The whole antenna is constructed on 20-mil Rogers RO4003 ($\varepsilon_r = 3.55$) substrate. The input impedance of a spiral antenna printed over a substrate with relative permittivity ε_r is calculated using [5]

$$z_{in} = \frac{z_{freespace}}{\sqrt{\varepsilon_{eff}}}(\varepsilon_{eff} = (1 + \varepsilon_r)/2) \tag{8}$$

The initial feeding network of SAW antenna consists of four 50 Ω semi-rigid coaxial cables soldered together, named bundle of cables. The inner conductor of each coaxial cable is connected to the SAW arms. This method increases the impedance among inner conductors [5]. This method improves the impedance matching of the antenna.

Simulation results show that, the antenna performs well over 4.6–11.4 GHz. Due to beamformer availability, measurements of antenna are presented at 5.8–10 GHz band in different modes (Fig. 10). The measurement response of constructing antenna is calculated at 30° theta angle. These figures prove dual circular polarisation and wideband properties of SAW antenna. As expected, the measured cross-polarisation of the antenna in difference mode is increased in comparison with other modes. Gain reduction, as shown in this figure, has happened due to ohmic loss of coaxial cable, SMA connectors and the feeding network. Better operation is expected by measuring it with wideband beamformer.

Measurement result of reflection coefficient for antenna is presented in Fig. 11. The S_{11} is <10 dB for most of the points. As expected, the reflection coefficient jumps above −10 dB at some frequencies. Better impedance matching can be achieved by using

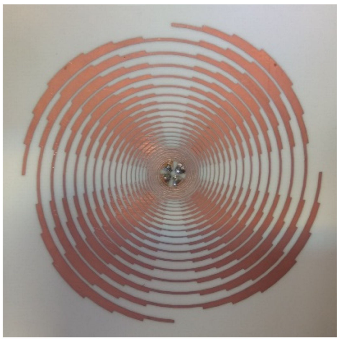
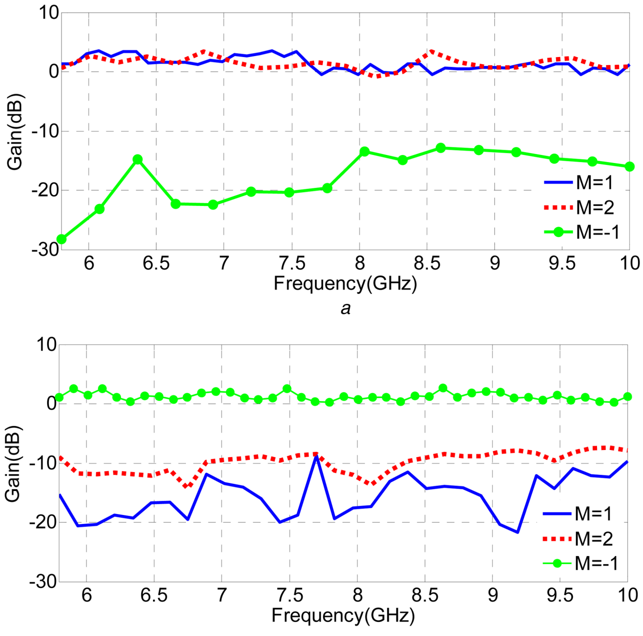


Fig. 9 *Photograph of constructed SAW antenna (EXP = 1.5, m = 4, n_s = 7, R_{out} = 7 cm)*



a

b

Fig. 10 *Constructed SAW antenna gain pattern in different mode*
(a) *RHCP,* ***(b)*** *LHCP*

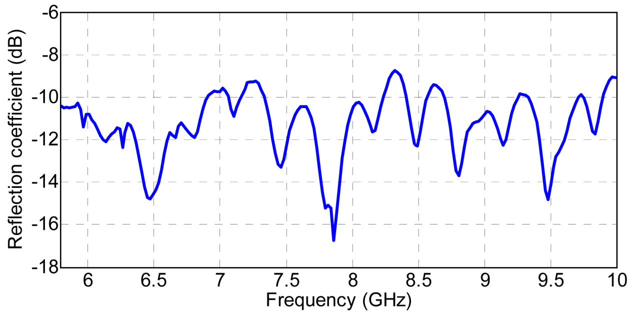


Fig. 11 *Reflection coefficient of constructed SAW antenna*

impedance matching methods such as the tapered transmission line introduced in [18]. Higher operating frequency leads to smaller stair width and height of the initial turns in the SAW antenna and causes some difficulties in the antenna construction process on the substrate. Consequently, no attempts to use matching baluns were undertaken and coaxial cables are used in this structure.

6 Conclusion

The SAW antenna is a new geometry for measuring dual circular polarisation and estimating the AOA instantaneously, providing that the frequency is known.

Stair discontinuities in the arm widths of SAW antenna generate a circular beam in the counter wrapping direction of the spiral arms. Comparing to MAW antenna, the cross-polarisation of SAW antenna is decreased in difference mode, which in turn improves the purity of circular polarisation. Furthermore, high n_s in SAW antenna decreases the high variations of the antenna input impedance.

Generally, similar treatments arise for MAW and SAW antennas in some characteristics. The major feature of the SAW antenna considered by the manuscript is the difference mode improvement among the wideband dual polarised antennas.

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