Design and Implementation of a Planar Slot Antenna for SSR

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Abstract— A useful, low cost, low complexity, and one layer microstrip slot L band antenna for secondary surveillance Radar (SSR) application is presented. The printed circuit feed network is a rat-race divider to create sum and difference ports and sixteen unequaled power dividers to satisfy the Chebyshev distribution. The feed network has an equally length parallel structure that create constant group delay in all output ports and wide frequency bandwidth. The suggested structure is a one-layer slot array of 2×8 slot elements that are fed with a microstrip corporate feed network. To improve total frequency bandwidth the slots are designed with unequal lengths. A substrate with low permittivity is used to decrease the side lobes. A $2:1$ VSWR bandwidth of 9.4% is achieved with the presented geometry in simulation to cover the 1030 ± 10 MHz transmit and the 1090 ± 10 MHz receive frequency band. The antenna gain for the sum pattern is 18.5 dB and 19 dB at 1030 MHz and 1090 MHz, respectively with a 3 dB beam width of 52° in elevation and 9.5° in azimuth. The difference has a -19 dB null at the peak of the sum pattern and an acceptable pattern against the sum pattern for SSR applications. Furthermore, the antenna has no need of the back fill antenna to eliminate the back lobe, which is critical for SSR applications. Its low complexity structure makes it appropriate for many radar applications.

1. INTRODUCTION

The Secondary surveillance radar (SSR) mechanism is based on sending a pair of signals at the frequency of 1030 MHz for interrogation and receiving a pair of signals as an answer at 1090 GHz [1]. SSR antennas are built in the form of planar or cylindrical array [2]. Reflector and multi-layer antennas are the most common SSR antennas in the literatures that have some disadvantages like complexity and being bulky [3, 4]. One layer microstrip array antennas which is proposed in this work, are the useful antennas in mass production because of their advantages like easily printed, light weight and low cost which makes them suitable for radar applications. However they have some disadvantages like narrow bandwidth and high side lob level. To enhance the bandwidth, many attempts have been done in microstrip field. One method of increasing the bandwidth for the microstrip antennas is using stacked elements [5]. [6] proposed a stacked patch array of 1×8 elements with 14 dBi gain and the SLL of -14 dB, which is not enough low to provide the Side Lobe Suppression (SLS) for the SSR [1]. In addition using stacked element increase the complexity of the system. In this paper a slot array antenna for the secondary surveillance radar application is presented. The antenna structure against the stack patch antenna is very simple. The fed slot antenna could increase the bandwidth in addition of reducing the antenna size. However, the fed slot antennas produce back radiation. To omit the back-lobes in the microstrip antennas, a metallic box is used behind the antenna. This technique is used to enhance the performance of the proposed antenna against with standard SSR antenna. The feed network has an equally length parallel structure that create constant group delay in all output ports and so cause wide frequency bandwidth. At first the performance of the SSR is described. Then the proposed antenna parts such as: single element, the sum pattern, the difference pattern and the feed network is presented. Finally the simulation results using in 3D EM simulation software High Frequency Structure Simulator (HFSS) are presented. The substrate that is used in the design is Rogers RT Duroid5880 with the dielectric constant of 2.2 and the thickness of 0.787 mm. Also the conductor cladding is about 17 μm.

2. ANTENNA CONSIDERATIONS

The SSR uses three impulses $P1$, $P2$ and $P3$ for the interrogation. $P1$ and $P3$ are sent by a directional antenna and $P2$ is sent after $P1$, by a special Omni directional antenna (Fig. 1). The configuration of these impulses provides the needed information for the transponder; with rational comparison between pulses $P1$ and $P2$, the transponder will recognize whether the signal is sent by a main lobe or side lobe of the SRR antenna. In the case of sending by a main lobe, it will respond. Typically, if $P1 > P2 + 9$ dB the transponder will respond to the antenna but if $P1 < P2$ it will not respond. Otherwise, it will respond or not respond depending on the transponder characteristics.

Figure 1: The relative strengths of the impulses $P1$, $P2$ and $P3$, adapted from [10].

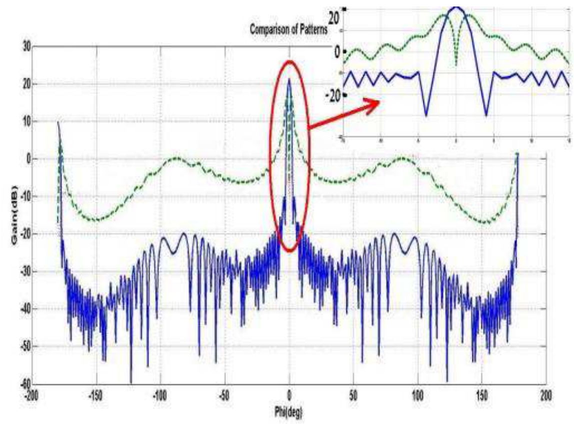

Figure 2: Typical Σ and Δ patterns.

The timing between pulses $P1$ and $P3$ shows the request content information [7]. The SSR antenna must contain of two special patterns: sum pattern (Σ) and difference pattern (Δ). Fig. 2 shows a typical sum and difference pattern. Two pulses $P1$ and $P3$ are sent by the sum pattern and pulse $P2$ is sent by the difference pattern. The Σ pattern is a directional pattern which should provide 14–16 dBi gain and 3 dB bandwidth of about 10° [1]. Typically, the sidelobe level of the Σ pattern is -20 to 30 dB [1]. To increase the accuracy, the beam width in azimuth should be narrow but in elevation should be wide to cover a large scan area. To increase the resolution in azimuth and also to enhance the dynamic range of the transponder receiver difference pattern has a null, as it is shown in Fig. 2.

3. ANTENNA DESIGN

3.1. Basic Element Design

The array element designed based on the requirement of frequency bandwidth, beam width, desired radiation patterns in E- and H-planes, compatible with microstrip structures and low mutual coupling for realizing an ultimate low side lobe pattern with vertical polarization. A slot resonated by a feed line proposed for array is shown in Fig. 3. To provide the characteristic impedance of 50 Ohms, the feed width considered 2.4 mm. The slot length (Ls) roughly is equal to $\lambda g/2$ to determines the resonate frequency at 1060 MHz [8]. As shown in Fig. 3, the slot size is 153×7.6 mm ($Ls \times Ws$). The parameter T, which is the distance from the end tip of the line to the slot (T), is equal to $\lambda g/4$ (34 mm). Finally, the L parameter, the offset from the end tip of the slot to the feed line achieved by optimization, about 42 mm. Figs. 4 and 5 show the simulation results of the slot antenna, performed by HFSS. Fig. 4 shows the parameter S_{11} of the slot element which is about -10 dB at 1.06 GHz. Fig. 5 shows the radiation pattern of the element. As discussed in the previous

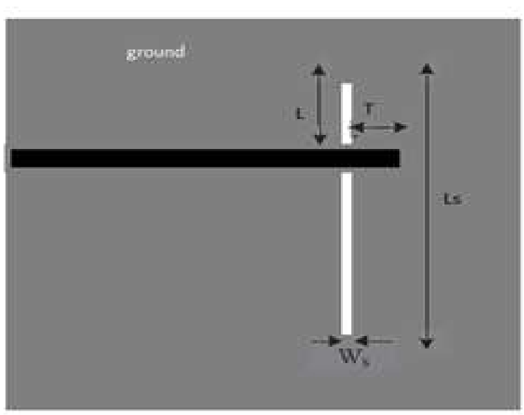

Figure 3: Microstrip fed slot antenna.

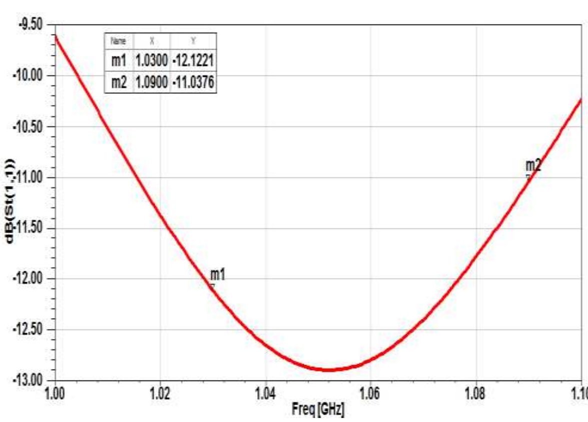

Figure 4: Return loss of the slot antenna.

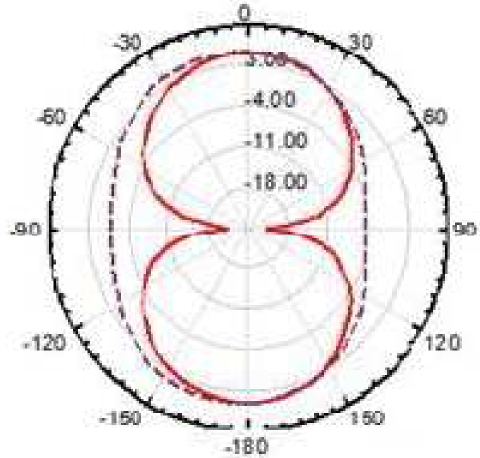

Figure 5: Radiation pattern of the slot antenna (the red line is phi = 0 and the black line is phi = 90).

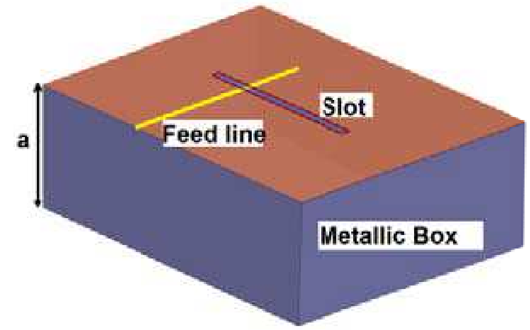

Figure 6: Metallic box behind the slot element.

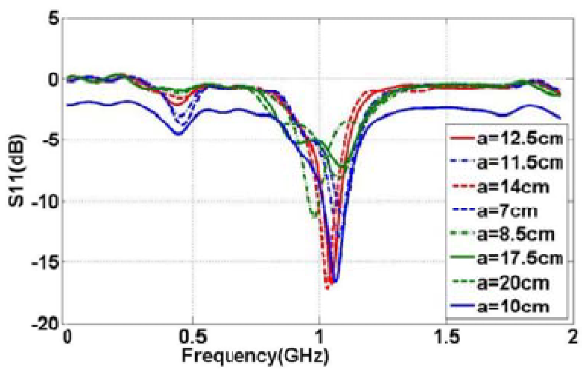

Figure 7: Optimization of the height of the metallic box against slot return loss.

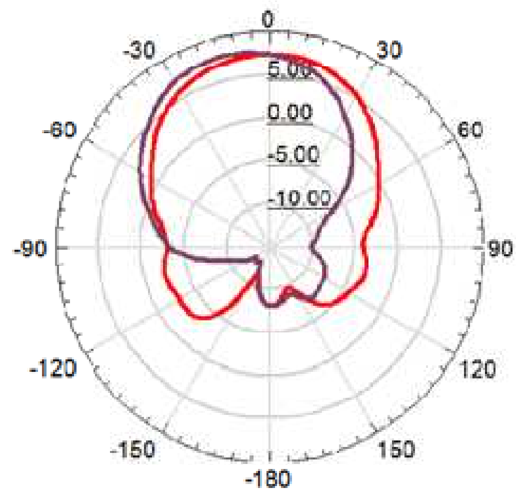

Figure 8: The single slot radiation pattern with the cavity of height 10 cm (the red line is phi = 0 and the black line is phi = 90).

section, sum pattern has to be a directional one. But this pattern has a back-lobe radiation around −3 dB. To improve the performance of the element, a back-lobe suppression technique is proposed by using a metallic box (Fig. 6). This box can eliminate the radiation from the back of the antenna by reflecting the backward radiation in the forward direction. The box height should be around $\lambda_0/4$ to reflect the back-lobe with 180° shift in phase. Fig. 7 shows the optimization process of the box height to obtain the best performance. 10 cm height resulted in minimizing the back-lobe and obtaining the S_{11} less than 10 dB at the 100 MHz bandwidth around the center frequency. Fig. 8 shows the radiation pattern of a single element after locating the metallic box. It shows that the back-lobe is minimized down to −17 dBc and the gain is improved up to 7 dB.

3.2. Array Design (Sum and Difference Pattern)

The design is considered a planar array with separable Dolph-Chebyshev distribution in which the elements are arranged in a rectangular grid, with a rectangular boundary. The array should be capable of generating both difference pattern as well as the sum pattern so an even number of elements should be chosen in each dimension. With the method which is discussed in [9], the number of elements are obtained 16 (2×8) with space of about 250 mm and 150 mm along X and Y axis respectively. The normalized Dolph-Chebyshev current distributions for −30 dB SLL are obtained as 1; 1.30; 1.78; 2.06; 2.06; 1.78; 1.30; 1.

To solve the frequency bandwidth limitation, the slot elements are designed with different length (about ±%5 tolerances in length). The Δ pattern is obtained by feeding the left and right sides of the antenna with 180 degrees difference in phase which creates a null in broadside of the Δ pattern.

3.3. Feed Network

The series and parallel feed are two types of feeds architectures. The in-line feed array occupies the smallest space with the lowest insertion loss, but generally has the least polarization control and the narrowest bandwidth. In contrast the parallel feeds have more insertion loss but their bandwidth is more than series feeds. So in the array antenna, the parallel feed is chosen. The first power divider is a rat-race hybrid with equal power split to feed two antenna halves. A ratrace coupler is used to provide in phase and 180 out of phase dividing/combining to create sum and difference patterns. Then to feed the 2×8 elements, fourteen T-junction power dividers are used which create a 1×16 power dividing with Chebyshev distribution. Fig. 9 shows the width of each power divider calculated in Advanced Design System (ADS) to satisfy the currents calculated in previous section. All paths from sum ports to slot elements must have equal length because in this situation the parallel feed network has constant group delay and wide frequency bandwidth as a result. So the branch of the last power divider is blended to satisfy this condition which is shown in Fig. 10.

4. SIMULATION RESULTS

Figure 11 shows the radiation pattern of the complete array antenna at 1030 MHz considering the effect of coupling and the feed network. It shows 18.5 dB gain for the main $\sum$ beam and 14 dB gain for the Δ beam. As it is shown the side lobe level of the Δ pattern is at least 4 dB more than $\sum$ one in full azimuth coverage angle, which are corresponds to the mentioned expectations. So it is not necessary to have back lobe antenna that is critical for SSR antennas. The SLL for the $\sum$ pattern is optimized to be minimized down to -22 dB. Fig. 12 shows the radiation pattern of the array antenna at 1090 MHz with 19 dB gain for the main $\sum$ beam and 15 dB gain for the Δ pattern. The side lobe level of the Δ pattern is also more than $\sum$ one but it is not necessary for

Figure 9: A part of feed network ($W1 = 10$ mm, $W2 = 0.5$ mm, $W3 = 4$ mm, $W5 = 7$ mm, $W6 = 2.4$ mm).

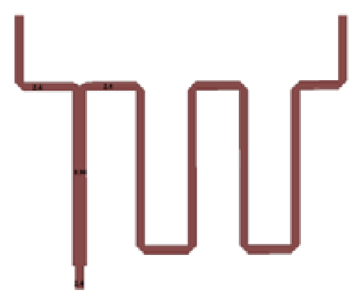

Figure 10: The last power divider schematic.

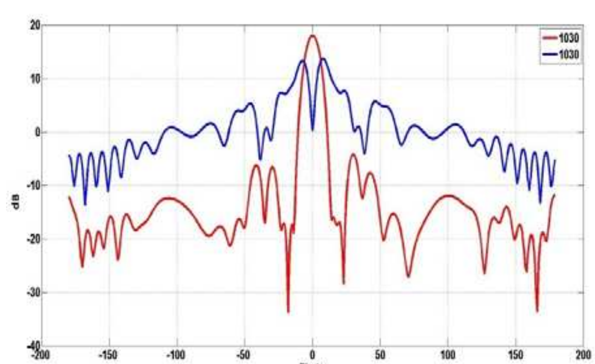

Figure 11: The radiation pattern of the array antenna with the center frequency of 1030 MHz.

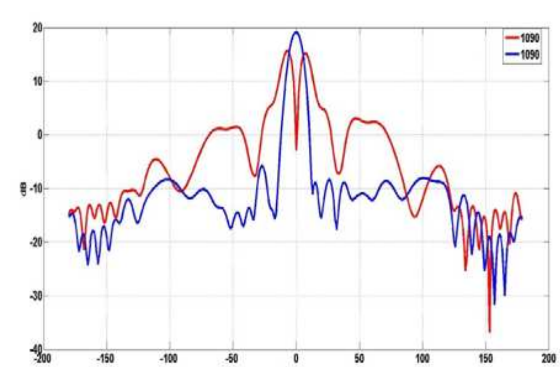

Figure 12: The radiation pattern of the array antenna with the center frequency of 1090 MHz.

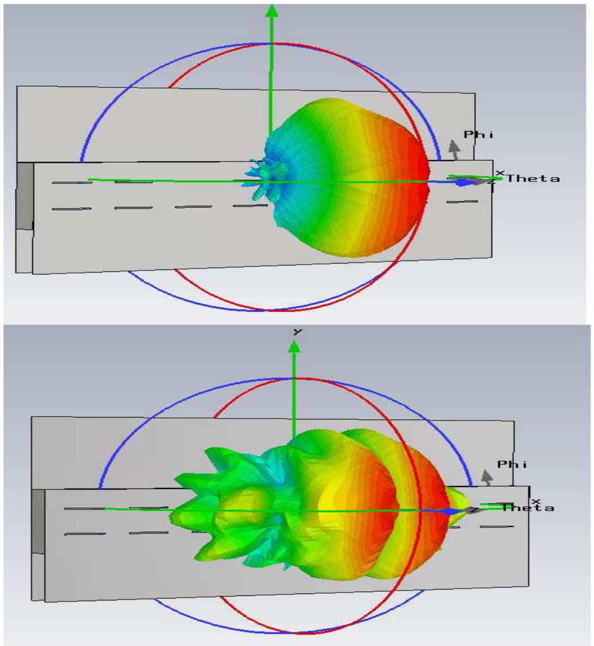

Figure 13: 3D sum and difference pattern of the array antenna at 1030 MHz.

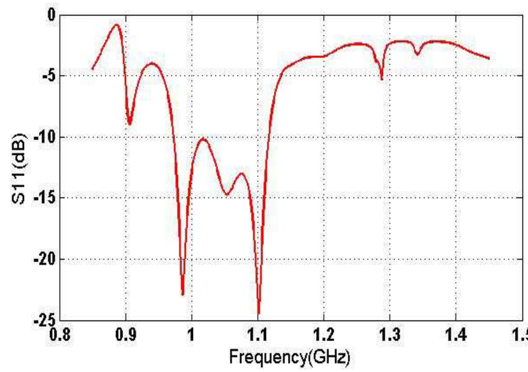

Figure 14: Simulated S_{11} of the 2×8 SSR antenna.

Table 1: Total characteristic of the proposed antenna vs goal values. The metallic box causes gain differences between desired and designed antenna.

Features	Unit	Designed Value	Goal Value
#Channels (Sum/Difference)	-	2	2
Frequency Range	MHz	1030 ± 5, 1090 ± 5	1030 ± 5, 1090 ± 5
Polarization	-	Vertical	Vertical
Sum Gain	dB	18.5	16
Sum Azimuth SLL	dB	-23	-25
Sum Azimuth BLL	dB	-28	-30
Difference Null	dB	19	20
Difference Coverage	dB	> 4	> 4
Sum Azimuth B.W	Degree	9.5	11
Sum Elevation B.W	Degree	52	50
Size	cm^3	$200 \times 10 \times 60$	
Gain at Elevation Angle $(-20°, -40°) + 5$ dB $>$ maximum Gain			
Gain at Elevation Angle $(\pm 60) + 12$ dB $<$ maximum Gain			
Gain at Elevation Angle $(\pm 90) + 18$ dB $<$ maximum Gain			
Gain at Elevation Angle $(\pm 145) + 28$ dB $<$ maximum Gain			
Back lobe $+ 30$ dB $<$ maximum Gain			

difference pattern in 1090 MHz to cover sum at least 4 dB, because at this frequency the antenna has only receiving. Fig. 13 shows the 3D pattern of the array antenna in 1030 MHz. The return loss of antenna is shown in Fig. 14 which is better than -10 dB in the antenna bandwidth. The total characteristics of the desired and designed antenna are shown in Table which show close agreement.

5. CONCLUSION

A useful, one layer, low cost, low complexity, wideband 2×8 planar microstrip antenna array was presented to operate as SSR antenna in 1030–1090 MHz. The basic array element was designed and optimized by using microstrip fed slot antenna. The feed was designed with a ratrace and 14 power dividers. To improve the frequency bandwidth of the proposed antenna, the slot elements were considered unequal length and the parallel feed was designed to be constant group delay. Also to enhance the antenna gain and to reduce BLL a metallic box is used. As discussed, one of the most advantages of this antenna is no need to a back fell antenna. The antenna gain for the sum pattern was 18.5 dB and 19 dB at 1030 MHz and 1090 MHz, respectively with a 3 dB beam width of 52° in elevation and 9.5° in azimuth. The difference has a −19 dB null at the peak of the sum pattern. A 2 : 1 VSWR bandwidth of 9.4% is achieved to cover the 1030 ± 10 MHz transmit and 1090 ± 10 MHz receive band.

REFERENCES

1. Vladimir, S., et al., "Secondary surveillance radar antenna [antenna designer's notebook]," *Antennas and Propagation Magazine*, IEEE 55.2, 2013.
2. Kumar Sharma, A., C. K. Kumar, and A. Mittal, "EM coupled L-band antenna array for secondary surveillance radar," *Europea Microwave Conference, 2009, EuMC 2009*, 1465–1467, Sep. 29, 2009–Oct. 1, 2009.
3. Foster, P. R., M. W. S. Grigson, and C. W. R. Wheatley, "D band IFF for army air defence systems," *Radar 97 (Conf. Publ. No. 449)*, 705–709, Oct. 14–16, 1997.
4. El, Y. M., M. Himdi, and J. P. Daniel, "Aperture-coupled microstrip antenna for dual frequency operation," *Electron. Lett.*, Vol. 29, 1506–1508, 1993.
5. Lee, R. Q., K. F. Lee, and J. Bobinjak, "Characteristic of a two layer electromagnetically coupled rectangular patch antenna," *Electron. Lett.*, Vol. 23, No. 20, 1070–1072, Sep. 1987.
6. Yashimura, Y., "A microstrip slot antenna," *IEEE Trans. Antennas Propagat.*, Vol. 29, 2–24, Jan. 1981.
7. Sharma, S. K., N. Jacob, and L. Shafai, "Low profile wide band slot antenna for wireless communications," *Proc. IEEE AP-S Int. Symp.*, 390–393, 2002.
8. Stevens, M. C., *Secondary Survillance Rada*, Artech House, 1936.
9. Elliott, R. S., *Antenna Theory and Design*, John Wiley & Sons, Inc., 1998.