An oscillating active integrated antenna (AIA) with a switchable pattern among sum or difference is reported here. The AIA design consists of a passive feedback network and an active device. A two-port, two-element patch array coupled electromagnetically through T-shaped microstrip lines is integrated into the feedback path of the oscillator circuit. This two-port network acts as a radiator and frequency-selective network for the oscillator circuit. The proposed AIA can switch in two different radiation pattern states by using p-i-n diodes. In the difference pattern, oscillating AIA has a measured null depth of $-19.86\,\text{dB}$ from the peak. The measured phase noise for both patterns is better than $-105.1\,\text{dBc/Hz}$ at a 1-MHz offset from the oscillation frequencies. The dc-to-RF efficiencies for both pattern states are better than 20%. The proposed design is suitable to cover the space in a more efficient manner by generating the pattern among broadside or conical.

**KEYWORDS**
feedback antenna oscillator, microstrip patch antennas, reconfigurability, Wilkinson power divider

## 1 | INTRODUCTION

Active integrated antenna (AIA) design and their applications in various fields have received much attention in current years.\textsuperscript{1,2} Active antenna design techniques are useful in fields such as beam steering,\textsuperscript{3} beam switching,\textsuperscript{4} quasi-optical power combining,\textsuperscript{5} wireless power transmission, and charging. AIA consists of an active device, such as two- or three-terminal device and a passive network. In oscillating AIA, the passive network acts as a radiator and frequency selector. The development of AIAs with low phase noise has been reported in References 3, 4, 6, and 7. Various methods such as cross-coupled mechanism to get low phase noise, substrate integrated waveguide-based methods, and injection-locking techniques for developing AIAs were investigated earlier.\textsuperscript{8,9} Radiation efficiency of oscillating AIAs was enhanced using metamaterial resonators\textsuperscript{10}; a metamaterial resonator provides high quality factor to get good radiation performance of the circuit. Among the techniques, for a single oscillating active antenna unit, a feedback loop approach provides the lowest phase noise. At present, there is a demand for AIA with reconfigurable feature in many application scenarios to save cost, size, and space.

Several AIA designs with different radiation patterns, such as broadside, quasi-isotropic, and end-fire, have been realized in the literature.\textsuperscript{11} There are various techniques to switch the radiation pattern in active array systems such as coupled oscillator techniques and externally or mutually coupled techniques.\textsuperscript{9,12-17} Phase shifter less beam steering technique
has been implemented in Reference 17. In all these designs, radiation beam is steered at some angles in the broadside direction to cover the space. Another important area of research is to switch the radiation beam among sum (broadside) and difference patterns (conical). Beam switching among sum or difference pattern is useful in communication systems. Broadside and conical patterns are useful to cover the space efficiently. Pattern-switchable antennas with broadside and conical beams are able to control a main beam or null direction at a specific direction, as shown in Figure 1. These antennas can provide larger coverage by switching the beam in a particular direction. Conical patterns were obtained in References 18 and 19. Reconfigurable antenna with switchable broadside and conical beams has been demonstrated in References 20-26. Antennas reported in References 20-26 were passive structures; they were not capable of generating RF signals. AIAs are preferred over passive antennas because they do not need any RF source; they can generate the beams by applying dc supply. By adding active feature to these antennas, the design becomes complex. There is always a challenge to make such antennas planar and simple. Beam switching in active antennas was obtained previously by using complex structures. In monopulse radar, beam switching has been achieved by complex feeding structures. Those feeding structures were bulky because waveguide structures were used to feed the phased array antennas. Active antennas are suitable candidates to solve this problem. Beam switching has been obtained from AIAs by employing various techniques. Progressive phase shift is needed to switch the radiation beam among sum or difference patterns. To get the progressive phase shift in active phased arrays, oscillator circuits are mutually coupled via interinjection locking, and free-running frequency of each oscillator can be controlled. This mutual coupling affects the bandwidth and mutual synchronization between oscillators. Undesired modes are also generated by strong coupling among oscillator circuits. A transmitter with beam switching capability has been reported; phase shifts were obtained by combining the powers quasi-optically. In Reference 27, difference pattern was achieved by tuning the free-running frequencies of the oscillators but sum pattern has lower power level compared to the difference pattern. Later, the progressive phase was achieved by unilateral injection locking, and there is more freedom to control phase in the circuit by using unilateral injection-locking technique. In Reference 29, in-phase and out-phase oscillation modes were obtained by chip resistor and metal strip, respectively. Two identical oscillator units have been used to get switching in the radiated beams. It is difficult to maintain the identical performance from more than one oscillator units; also, the resistor degrades the noise performance of the circuits.

In this article, a different technique is used to switch the radiation pattern among sum or difference in oscillating AIA. Normally, the broadside radiation is generated from microstrip patch antenna resonates at the fundamental mode (TM_{01}), and the sum pattern is achieved by making an array of microstrip patches, while the conical pattern is obtained by different methods such as generation of higher order mode (TM_{02}) from microstrip patch. In this design, the conical pattern is obtained by two microstrip patches by canceling the fields in the broadside direction. In addition, one oscillator unit is used to get two switchable beams. No locking technique is used in this design, which may degrade the power and offset of the radiated beam. The proposed design is simple in geometry; phase shift is achieved by changing the field directions of the individual patch elements and it does not involve any coupling mechanism. In Reference 4, an idea has been proposed to get null in oscillating type AIA by adding a delay line (\lambda/2) to one of the patch elements. A null depth of −9.8 dB from peak was obtained in this case. In phased arrays, the power is fed to the antennas through phase shifters in such a way that the phase of the elements alters, and hence, beam switching is achieved from the circuit. A different

\textbf{FIGURE 1} Reconfigurable antenna with switchable pattern among broadside or conical beams
approach is proposed in this article to create the deep null and improve the nulling performance. Here, the patch elements are fed with same electric fields to get the sum pattern or with opposite electric fields to get the difference pattern.

This article is organized as follows. The proposed antenna configuration and its operating principle are described in Section 2. Measured and simulated results of the feedback network are discussed in Section 3. Section 4 describes the design of the proposed active antenna, and the performance in terms of radiation pattern, efficiency, and noise is discussed. The article is concluded with some advantages and applications of the design.

2 | ANTENNA CONFIGURATION AND OPERATING PRINCIPLE

2.1 | Two-port passive antenna design

For designing a switchable AIA, a passive two-port network is designed first. The geometry and photograph of a two-port network are illustrated in Figure 2. Microstrip patch elements are electromagnetically coupled on both sides through T-shaped 50-Ω microstrip lines. An array is formed by placing two identical patch elements with a separation of \( d = 11.5 \text{ mm} \). The power at the ports is distributed and combined using Wilkinson power dividers (WPDs). Two equal WPDs are designed with the help of standard equations. Eight p-i-n diodes (Model MA4SPS402) are used in the circuit to switch the radiation pattern among sum or difference. The proposed two-port network is designed on a 0.787-mm Rogers 5880 substrate with \( \varepsilon_r = 2.2 \) and \( \tan \delta = 0.0009 \). The biasing circuit consists of RF chokes (100 nH), dc block capacitors (10 nF), dc bias pad, and Agilent dc power supply (Model U8002A). The dimensions of a two-port network are \( g = 0.2 \text{ mm}, \ l_1 = 28.25 \text{ mm}, \ l_2 = 19.84 \text{ mm}, \ l_3 = 16.05 \text{ mm}, \ l_4 = 46.44 \text{ mm}, \ L_p = 18.32 \text{ mm}, \ L = 74 \text{ mm}, \ L_{wpd} = 12.45 \text{ mm}, \ t = 0.3 \text{ mm}, \ W_p = 18.32 \text{ mm}, \ W = 76 \text{ mm}, \ W_{50} = 2.4 \text{ mm}, \text{ and } W_{wpd} = 1.38 \text{ mm.} \)

2.2 | Operating principle

In state 1, diodes D2, D4, D5, and D8 are in forward bias (on state) and diodes D1, D3, D6, and D7 are in reverse bias (off state). In this case, power is coupled to the patch elements in such a way that the power is combined in the far field and maxima is formed in the broadside direction (\( \theta = 0^\circ \)). Two-port, two-element array is placed in the xy-plane and the radiation pattern is in the positive z-direction (broadside). To switch on diodes D2 and D5, a dc bias of 1.7 V is applied across Nodes A and B. Similarly, to switch on diodes D4 and D8, a dc bias of 1.7 V is applied across Nodes C and D. In state 2, diodes D1, D3, D6, and D7 are in forward bias (on state) and diodes D2, D4, D5, and D8 are in reverse bias (off state). In this case, the power is fed to the patch elements in such a way that the fields cancel and a null is obtained in the broadside direction. The current of 5 mA is required to turn on the p-i-n diode.

![Figure 2](image-url)  
Figure 2: Proposed two-port network: (A) geometry and (B) photograph
3 | RESULTS AND DISCUSSIONS

The simulations of two-port network were performed by CST.\textsuperscript{30} The equivalent model of the p-i-n diode in on and off states is shown in Figure 3. The parasitic inductances of the diode are ignored in the simulations. The reflection ($S_{11}$) and coupling ($S_{21}$) coefficients are depicted in Figure 4. At 5.2 GHz, the measured values of reflection coefficient ($S_{11}$) for sum and difference patterns are $-10.84$ and $-10.18$ dB, respectively. The measured values of transmission coefficient ($S_{21}$) for sum and difference patterns are $-5.19$ and $-5.08$ dB, respectively. The measured coupling phases (transmission coefficient phases) for sum and difference patterns are $-161.12^\circ$ and $-162.03^\circ$, respectively. The coupling phases are plotted in Figure 5. At design frequency (5.2 GHz), the difference in the measured coupling phase in both patterns is $1.08^\circ$. The coupling phase is measured at the ends of the WPD. The proposed two-port network gives almost the same

![Equivalent model of a p-i-n diode](image1)

**FIGURE 3** Equivalent model of a p-i-n diode

![S-parameters of a two-port network](image2)

**FIGURE 4** S-parameters of a two-port network for (A) sum pattern and (B) difference pattern

![Measured coupling phases](image3)

**FIGURE 5** Measured coupling phases of a two-port network
FIGURE 6  Normalized radiation patterns of a two-port network in the yz-plane

coupling phase at WPD ends as it is required for the oscillations in both pattern states. The radiation patterns of the proposed two-port, two-element patch array are measured in an anechoic chamber by terminating one of its ports to 50 Ω. The normalized radiation patterns for both states are plotted in the yz-plane, as depicted in Figure 6. The measured null depth in the difference pattern is obtained as −24.7 dB from peak. A two-port network is measured by taking a copper strip of 2 × 2 mm² instead of p-i-n diode. Next, an oscillating AIA is developed by integrating this two-port network into the feedback path.

4 | OSCILLATING AIA DESIGN

The layout of the circuit and its photograph are shown in Figure 7A,B, respectively. The dimensions of the proposed AIA are \( L = 96 \text{ mm}, L_{11} = 94 \text{ mm}, L_{12} = 88.5 \text{ mm}, L_s = 6 \text{ mm}, L_{as} = 11.3 \text{ mm}, L_{bsf} = 11.1 \text{ mm}, \) and \( W = 106 \text{ mm}. \) An n-channel heterojunction field-effect transistor (HJFET) NE3512S02 is biased in the unstable region. Two band-stop filters are integrated into shunt (before and after the active device), as shown in Figure 7A, with the circuit to remove unwanted resonances occurred at lower frequencies. The gain of the active device is large at lower frequencies; the circuit may oscillate at those lower frequencies. To prevent the oscillations at unwanted frequencies, band-stop filters are connected in shunt to the circuit. These band stop filters block other lower resonance bands and pass only 5.2-GHz band. The power of those unwanted frequency components is absorbed by 50-Ω resistors and terminated into the ground. The lumped inductors (50 nH) are used to bias the gate and drain of the active device. To separate the bias of p-i-n diodes and active device, two capacitors (10 nF) are connected between the feedback network and the active device. The complete AIA circuit is simulated in advanced design system by taking the design kit of the active device. The simulated values of loop gains for the sum and difference patterns are 1.001 \( \angle 0° \) and 1 \( \angle 0° \), respectively. The oscillation frequencies and powers for the sum and difference patterns are 5.24 GHz, 11.43 dBm and 5.245 GHz, 9.83 dBm, respectively. The loop gains and oscillation powers are plotted in Figures 8 and 9, respectively. The proposed AIA is fabricated on the same substrate specifications as a two-port network. The bias for the active oscillator circuit is \( V_G = -0.52 \text{ V}, V_d = 1.9 \text{ V}. \) The value of the drain current for both patterns is 16 mA.

The normalized radiation patterns of AIA for both states are plotted in the yz-plane, as shown in Figure 10. The null depth of \(-19.86 \text{ dB}\) is obtained in the difference pattern of the AIA circuit. In Figure 10, the measured peaks in the difference pattern of AIA are not same at \(+30°\) and \(-30°\), and null is not exactly at 0°. Similarly, in the sum pattern, the maximum is not exactly at 0°. This is due to the unequal coupling of powers to the patch elements. A single p-i-n diode has a 5-Ω resistance in the on state; it gives a 1.5-dB loss (|S_{21}|) in the transmission patch. This loss can be reduced using p-i-n diodes with lower series resistance (\(R_{on}\)).

The effective isotropic radiated powers (EIRPs) are calculated by using the Friis equation

\[
\text{EIRP} = P_t G_t = \frac{P_t G_t}{G_t G_{rlc}} \left( \frac{4\pi R}{\lambda_0} \right)^2.
\]
The received powers for sum and difference patterns are $-35.25$ and $-55.08$ dBm, respectively. The gain of the horn antenna is 11 dBi at 5.2 GHz, the distance between the AIA circuit and horn antenna is 220 cm, $\lambda_0 = 57.69$ mm (free space wavelength), and $l_c = -7.5$ dB. EIRPs are evaluated from Equation (1) as $14.86$ dBm for the sum pattern and $-4.97$ dBm for the difference pattern. The gain of the transmitting antenna is calculated for both pattern states by using the standard approach. The calculated gains are 4.71 dBi for the sum pattern and $-15.67$ dBi for the difference pattern. The oscillation output powers ($P_t$) are calculated as $10.15$ and $10.70$ dBm for the sum and difference patterns, respectively. The measured oscillation frequencies for the sum and difference patterns are 5.214 and 5.219 GHz, respectively. Phase noise is measured using the N9010A signal analyzer with a resolution bandwidth of 100 kHz. The phase noise of the AIA circuit is shown in Figure 11. The dc power consumed by the active element was 30.4 mW in each state. To achieve one pattern state, the dc powers consumed by diodes were 17 mW for each state. DC-to-RF efficiencies are calculated as $29.30\%$ and $20.27\%$.
**FIGURE 9** Output power spectrum of the proposed active integrated antenna (AIA) for (A) sum pattern and (B) difference pattern.

**FIGURE 10** Measured normalized radiation patterns of the proposed active integrated antenna (AIA) in the yz-plane.

**FIGURE 11** Measured phase noise in both pattern states.
for sum and difference patterns, respectively. The performance of the proposed oscillating AIA is summarized in Table 1. Comparison of the performance with earlier reported articles are given in Table 2.

Various techniques were used to steer or switch the radiation beam in oscillating AIAs. In most of the designs, steering or switching was done by the coupling mechanism between more than one oscillator circuits. In these designs, identical performance is needed from each unit of oscillator circuits. Reconfigurability can also be achieved by changing the passive part (radiator) of the circuit using switches. These designs need only a single active element to switch or steer the beam. Beam switching was obtained in References 22-26; it was achieved with use of a coupling mechanism or mode switching between oscillator units. In this article, beam switching is obtained by changing the radiator characteristic.
In this design, the parameters that affect the radiation pattern (sum or difference) are less compared to other designs. Some offsets observed in the radiation pattern are because of p-i-n diodes. The performance can be improved by using high-quality p-i-n diodes ($R_{\text{on}} \sim 2 \Omega$), which have low insertion loss in the on state. Also, with a low value of resistance ($R_{\text{on}}$), the fields from patch elements would effectively get canceled, and as a result, null depth would be improved.

5 | CONCLUSIONS

An oscillating AIA with a switchable pattern among sum (broadside) or difference (conical) is reported in this article. The proposed AIA has two switchable patterns. In the difference pattern, a null is obtained with a value of $-19.86$ dB (normalized value). The proposed AIA has measured oscillation powers of 10.15 and 10.70 dBm at 5.214 and 5.219 GHz, respectively. The measured phase noises for both pattern states are better than $-105.1$ dBc/Hz at 1-MHz offset from the oscillation frequencies. The dc-to-RF efficiencies for both pattern states are better than $20\%$. The proposed design has a simple geometry and more freedom to switch the beam by changing the phase shifts, and it can be done by changing the lengths of the delay lines. This work can be extended to get sum and difference patterns in both azimuth and elevation planes by making $2 \times 2$ array of patches and appropriate phase shifters. The proposed design can generate and switch the beam and can efficiently provide beam coverage.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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