

# Optically-Switched Antenna with Parallel Photodiodes

Peiyong Lin and Jiangtao Huangfu\*

**Abstract**—A novel optically-switched antenna is proposed, in which a photodiode is embedded into an antenna radiator. In order to avoid the high loss problem in series structures for the integration of photodiodes and patch antenna, a photodiode parallel structure with sensitive radio frequency response is selected for the design. The status of the antenna while at work can be effectively adjusted by illumination. Its reflection coefficient and radiation gain vary with the exposure of photodiode to light illumination and non-illumination state. The simulation and experiment of this design at 1.52 GHz produce an obvious effect on light control with a maximum 6.6 dB gain variation on omnidirectional pattern. It is thus deemed suitable for speed measurement and occlusion detection in remote wireless sensor networks and other applications.

## 1. INTRODUCTION

In recent years, as wireless technology advances on a continued basis, the requirement of multi-state antenna is made increasingly demanding. As a flexible implementation method, controllable antenna has attracted widespread attention for study. Nowadays, high speed diodes are frequently applied in the structure adjustment and state control of antenna depending on its switching states [1–3]. For example, PIN diodes are used to enable the conversion of different beams and angles [4–6]. In [7–9], the antenna can function in different polarization directions by controlling diode that acts as a switch to adjust current distribution. Moreover, the resonant frequency and radiation characteristics of the antenna can be made changeable by the diode switch [10–13].

Electronic diode switches require circuit control, which is inevitable to cause electromagnetic coupling interference with the antenna. By contrast, the working mode of optically controlled antenna will eliminate the possibility of additional coupling and structure problems. Recently, some studies have been conducted where light is taken as a stimulus to exercise control over microwave signals [14–16]. Silicon material is often integrated into an antenna structure as an effective optical control method in antenna design for its light conduction characteristics. For example, a dual-band antenna is designed in [17] with silicon switches attached in series. A new resonance appears at 12 GHz with switches activated on the premise of the original working frequency 18 GHz. In [18], photoconductive plasma is integrated on semiconductor substrates for controlling reflection characteristics of antennas. In [19], a polarization reconfigurable antenna based on silicon optical switches is proposed. [20] applies silicon photonics technologies in fabricating waffle and waffle iron waveguides as leaky wave optical antennas with high gain.

Nevertheless, these designs of optical antennas necessitate special semiconductor processing of silicon switch, which is insignificant to the existing antenna design engineering. Photodiodes have been used in [21] as an optical switch connected in series between dipole arms of microstrip antennas, resulting in a shift of 100 MHz of resonant frequency and 1 dB fluctuation in  $S_{11}$  value. Another optically controlled Yagi-Uda antenna design [22] is transformed between two configurations by switching series

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photodiodes. The direction of maximum radiation of two states differs by  $180^\circ$  from one side to the opposite side on the radiation patterns. These mentioned designs realize the reconfiguration of frequency or radiation pattern through series connections. In contrast, the focus of this research is placed on how to design the optically controlled antenna with the existing optoelectronic devices aimed at significant gain variation on omnidirectional pattern.

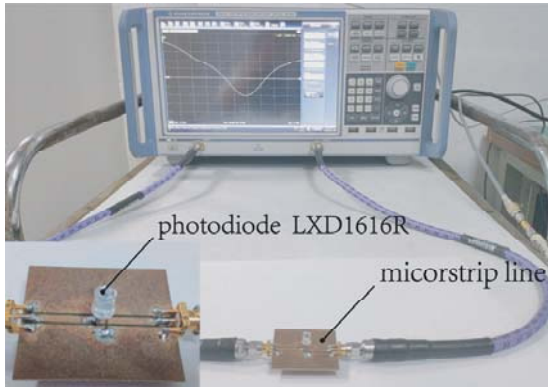
In this paper, a variety of optically-switched antenna integrated with commercial photodiode that relies on light to control the state of radio frequency radiation is designed. In the absence of light illumination, the antenna enters into an abnormal working state. Otherwise, the impact on the radiator would be mitigated as a result of photodiode functions. At this point, the antenna shifts to a highly efficient working state. Distinct from the method adopted in the traditional way of serial connection, the light-controlled diode here is grounded in parallel, thus preventing the high transmission loss caused by the diode itself at high frequencies. Measurement results confirm that a maximum 6.6 dB gain variation can be obtained on omnidirectional pattern by parallel connection.

## 2. PHOTODIODE MEASUREMENT

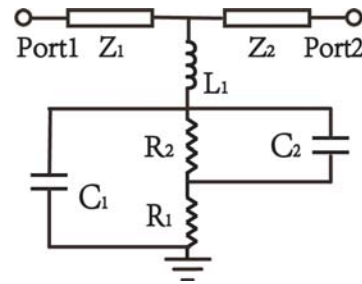
In order to identify the available light tunable components, the commercial package photodiode is connected to the microstrip line in parallel. As shown in Fig. 1, the microstrip transmission characteristics were measured under different lighting conditions. This coplanar microstrip is an FR4 substrate that is 2.1 mm in width and 1.2 mm in thickness. After selection and measurement, the photodiode LXD1616R allows the microstrip line to reach a  $-12$  dB insert loss around 1.52 GHz under both non-illumination and low-level illumination conditions. When white light illumination exceeds 800 lux, however, the impact of the photodiode on the microstrip is diminished, and the insert loss returns to zero, as shown in Fig. 3(a). It is worth noting that LXD1616R is unfit for the use in RF circuit previously with poor series RF characteristics. The RF equivalent circuit [23] of such a parallel photodiode is illustrated in Fig. 2, while the frequency response function of the circuit is shown as Eq. (1):

$$H(\omega) = \frac{Z_2}{Z_2 + Z_1 \left( Z_2 \frac{-\omega^2 R_1 R_2 C_1 C_2 + 1}{j\omega R_1 R_2 C_1 \left( \omega^2 L_1 C_1 \frac{L_1}{R_1 R_2 C_2} - 1 \right)} \right)} \quad (1)$$

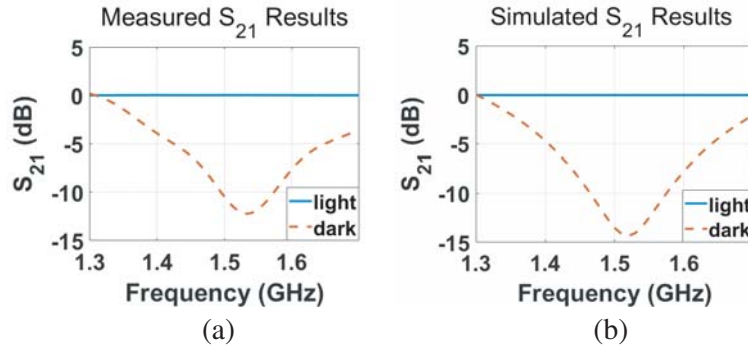
Among them,  $L_1$  is 4.21 nH;  $R_1$  is 460.05  $\Omega$ ;  $R_2$  is 1.19  $\Omega$ ;  $C_1$  is 52.01 pF;  $Z_1$  and  $Z_2$  are 50  $\Omega$  representing transmission line and port impedance;  $\omega$  is the angular frequency. Illumination leads to the photoelectric effect of the photodiode, thus causing significant changes in the parameters of



**Figure 1.** VNA measurement of microstrip line with LXD1616R photodiode.



**Figure 2.** Equivalent circuit of the microstrip line with parallel photodiode.



**Figure 3.** Measurement and simulation results of microstrip line: (a) Measurement of microstrip line under different lighting conditions; (b) Simulation of microstrip line under different lighting conditions.

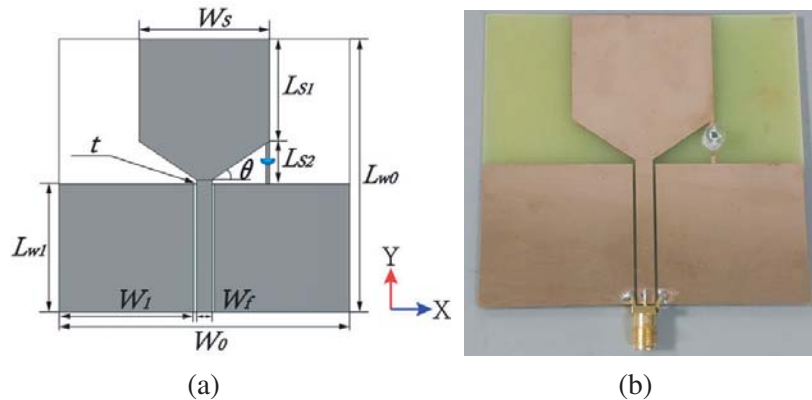
equivalent circuit, especially  $C_2$ . It is 2.61 pF under non-illumination condition. Then, it decreases to 0.01 pF with illumination at 1.52 GHz, and the transmission power shows a sharp decline.

The simulation of the parallel photodiode is conducted using the equivalent structure shown in Fig. 3(b). It approaches the experimental  $S_{21}$  results. The working frequency is around 1.52 GHz under illumination condition, while the transmission efficiency is significantly higher than under that non-illumination condition. Meanwhile, the response time of LXD1616R is less than 50  $\mu$ s during experiment, as a result of which the rate of periodic change in optically switching frequency can reach 20 kHz.

### 3. ANTENNA DESIGN AND APPLICATION

With the aforementioned method adopted, an optically-switched patch antenna is designed. The photodiode is connected to a radiator in parallel to affect the working state of antenna, rather than the traditional design method of inserting it in series. Fig. 4(a) shows the diagram of its structure. The parts in black shown in Fig. 4(a) are made out of copper, corresponding to the bronze parts in Fig. 4(b), while the part in white shown in Fig. 4(a) serves as the FR4 substrate, corresponding to the part in yellow shown in Fig. 4(b). The thickness of the substrate is 1.2 mm; dielectric constant is 4.6; the angle  $\theta$  between radiator and the ground is 38.96°. In order to achieve the optically tunable effect, a photodiode is deployed between the corner of the antenna radiator and ground with a connecting line. The detailed dimensions are listed in Table 1.

The electromagnetic simulations of the antenna are conducted with the assistance of CST Microwave

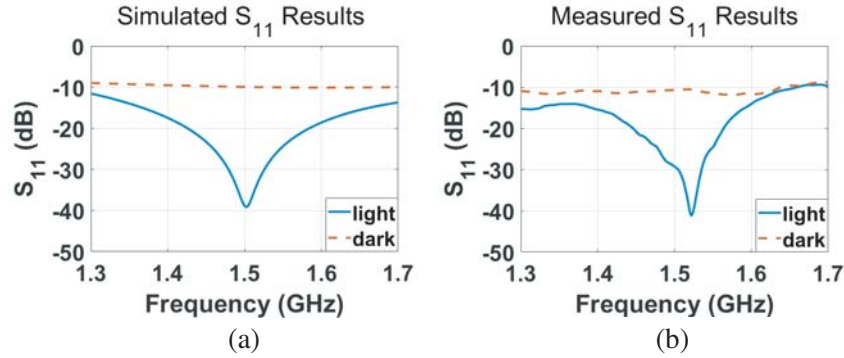
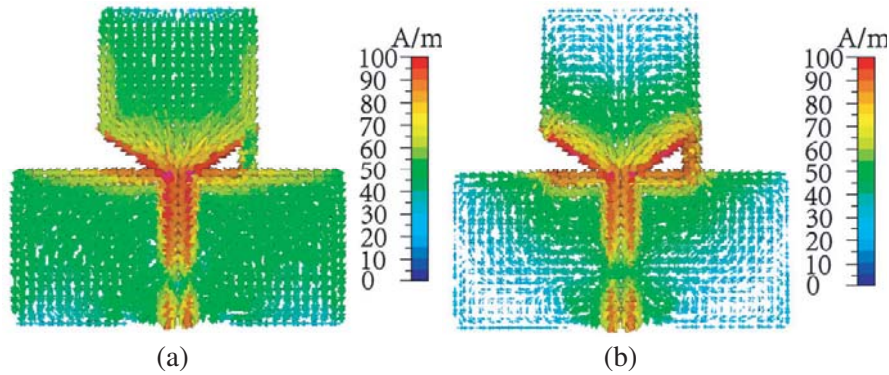


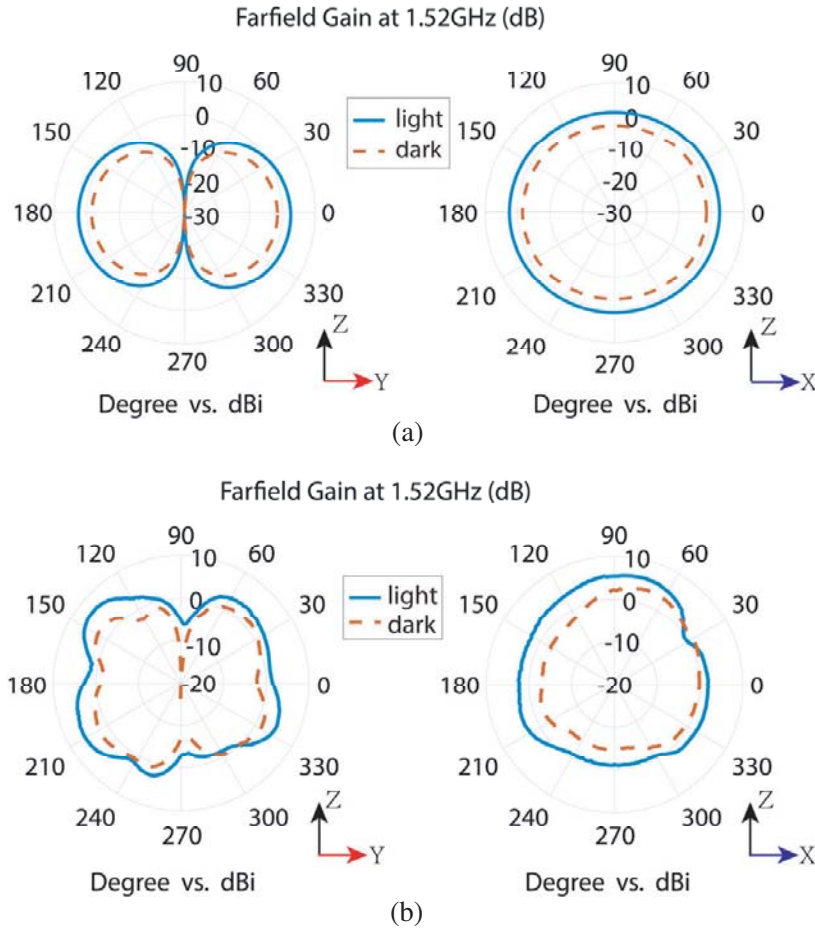
**Figure 4.** The specific structure diagram of the antenna: (a) Dimensioning drawing of the antenna; (b) Antenna photographs.

**Table 1.** Detailed dimensions of the antenna.

Parameters	VALUES (MM)
$W_s$	35.39
$L_{s1}$	27.89
$L_{s2}$	11.21
$W_0$	78.59
$W_1$	37.03
$L_{w0}$	74.10
$L_{w1}$	35.00
$W_f$	4.43
$t$	0.20

Studio. Besides, the photodiode equivalent circuits are introduced into the full-wave simulation models, which are equivalent to the state of the photodiode under light illumination condition and non-illumination condition. In illumination state, the working frequency of the antenna is around 1.52 GHz, as shown in Fig. 5(a), with  $S_{11}$  denoted as a solid line. The current distribution on the antenna is simulated as presented in Fig. 6(a). There is an effective current spreading on the radiator with few current through photodiode. When the photodiode is not exposed to illumination, reflection increases,

**Figure 5.** Simulation and measurement results of  $S_{11}$  parameters for the proposed antenna: (a) Simulation results; (b) Measurement results.**Figure 6.** Simulated results of current distribution: (a) Current distribution under light illumination condition; (b) Current distribution under non-illumination condition.



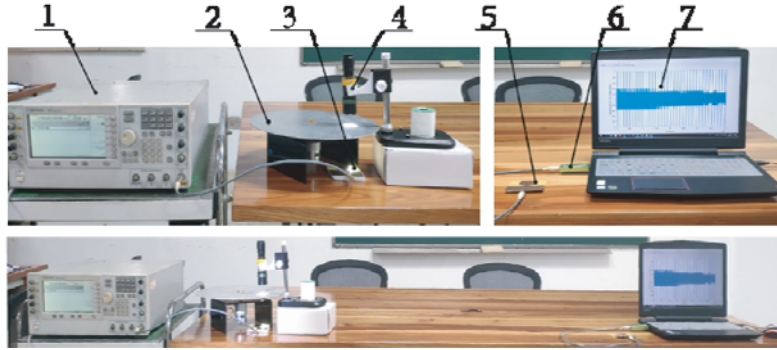
**Figure 7.** Simulated and Measured normalized antenna radiation patterns for two planes: (a) Simulation results of  $YZ$ -plane and  $XZ$ -plane; (b) Measured results of  $YZ$ -plane and  $XZ$ -plane.

and the antenna ceases to function as shown by a dashed line in Fig. 5(a). In this state, the current on the radiator is greatly reduced due to the influence of photodiode as revealed in Fig. 6(b). The patterns of radiation gain are shown in Fig. 7(a), with a maximum gain difference of 4 dB between two states in  $YZ$ -plane and  $XZ$ -plane.

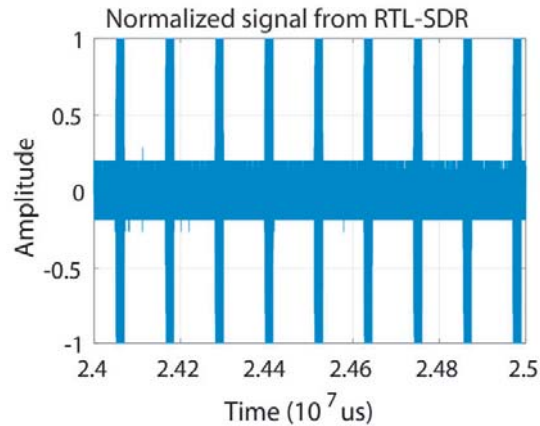
This antenna is fabricated as illustrated in Fig. 4(b). The position of the photodiode on the antenna is illuminated by a 1000 lux white light source. As indicated by the measurement  $S_{11}$  value of solid line in Fig. 5(b), the antenna functions at 1.52 GHz and produces a satisfactory matching effect when the photodiode is illuminated. Judged on the  $S_{11}$  value shown as a dash line in Fig. 5(b), it can be known that the absence of light illumination results in the decline in the radiation performance of the antenna. The radiation gains are also measured as shown in Fig. 7(b) with a maximum gain difference of 6.6 dB between two states in  $YZ$ -plane and  $XZ$ -plane, revealing a similar gain variation effect to the simulation results. Compared with other optically tunable antennas integrated with series diodes in [13–17] with the purpose of reconfiguration of spectrum and radiation patterns, the result of proposed antenna obtains a significant gain variation covering over  $270^\circ$  on omnidirectional pattern.

Additionally, a wireless transmit-receive experimental system was constructed to facilitate the rotation speed measurement, involving light source, a spinning disk, a 1.52 GHz RF signal source with an optically-switched antenna and an RTL-SDR receiver with a 1.52 GHz patch antenna, as illustrated in Fig. 8. Illumination hits the photodiode through a hole drilled on the rotating disk, thus causing a significant gain lift in radio frequency radiation. With an actual distance of 10 meters between two antennas, they are placed in parallel. The significant fluctuations measurement signal is shown in Fig. 9 with the periodic change in lighting intensity conditions. It can be found that the receiver is efficient

in sensing the modulation of the illumination state of the optically-switched antenna, based on which the rotation speed of the disk can be calculated through the period of fluctuation. The experimental rotation speed obtained using this method is compared with the actual speed, as shown in Table 2. Then, the error rate is found to be less than 1.44%. The design is applicable not only under normal indoor environments in the absence of strong background light, but also outdoor with box to resist light interference.



**Figure 8.** Antennas and transceiver system: 1: 1.52 GHz RF signal source; 2: spinning disk; 3: optically-switched antenna; 4: light source; 5: 1.52 GHz patch antenna; 6: RTL-SDR receiver; 7: signal from RTL-SDR.



**Figure 9.** Normalized signal from RTL-SDR with periodic light illumination.

**Table 2.** Comparison of the measured rotation speed with the real speed.

Real Speed (RPM)	Measured Speed (RPM)	Error Rate (%)
90	91.3	1.44
123	121.4	1.30
237	235.1	0.80
320	322.4	0.75
465	461.6	0.73
625	619.5	0.88
925	930.7	0.62
1290	1296.2	0.48

#### 4. CONCLUSION

An optically-switched patch antenna is designed for the introduction of a parallel photodiode into a radiator. Through simulation and experiments, it can be determined that there is a significant change in antenna gain performance on omnidirectional pattern under illumination and non-illumination conditions. Due to such characteristics, the monitored target such as spinning disk or other periodicity movement objects can be positioned between the light source and the optically-switched antenna. If the light received by the photodiode is repeatedly blocked from the target, the swing frequency or rotation speed of the target can be obtained remotely through the periodic change in the amplitude of transmitted signal.

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