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RESEARCH PAPER

Optically controlled UWB antenna using photonic crystal waveguides

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This paper presents a new optically controlled reconfigurable ultra-wideband antenna using reconfigurable optical router with photonic crystal substrate. The proposed antenna has three optical switches. The optical switches are made by placing silicon wafers over three slots etched on the resonator. The coplanar fed microstrip antenna can work at eight modes using optically controlled switches. This design proposes triple narrow notched bands at center frequencies 3.5 GHz "WiMAX", 5.5 GHz "WLAN" and 8.4 GHz "X-band satellite communication". The proposed antenna satisfies the voltage standing wave ratio requirement of <2 in the frequency band between 2.6 and 11.8 GHz except for the three rejected bands. According to the incident light, the physical properties of these switches can be changed from an insulator state (OFF state) to a near-conducting state (ON state). The incident light is coupled to the optical switches using a reconfigurable optical router. The proposed antenna provides high gain, and high efficiency all over the frequency band excluding the rejected bands.

Keywords: Antenna design, Modeling and measurements, Microwave photonics

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I. INTRODUCTION

The ultra-wideband (UWB) planar antennas play an increasingly important role in current UWB systems due to its attractive merits, such as small size, low cost and ease of fabrication. Over the commercial frequency band from 3.1 to 10.6 GHz approved by FCC [1] there are some other existing narrowband systems, such as Bluetooth application at center frequency of 2.45 GHz, WiMAX system (3.4–3.7 GHz), C-band satellite (3.7 to 4.2 GHz), and Wireless Local Area Network (WLAN 5.15–5.35 GHz) and "X-band satellite communication systems" (7.25–7.75 GHz downlink and 7.9–8.4 GHz uplink) [1]. To avoid possible interference between UWB system and these bands it is desirable to design UWB antennas with notched bands. Electronic switches were mounted across or along the resonators to activate the corresponding notched band. Microwave switches have been applied in designs to control antennas, filters, phase shifters, and couplers [2–6]. The research of optically controlled microstrip switches started in 1970s and is continuing throughout to today. Advantage of optically controlled microwave circuits is high level of isolation between the controlling electronic circuit and the microwave circuit [6–7]. Optical switches were introduced in the designs for achieving frequency and beam reconfigurable antennas [7–9].

II. COMPLETE SYSTEM OF OPTICALLY CONTROLLED UWB ANTENNA WITH OPTICAL ROUTER

Figure 1 illustrates the designed optically controlled microstrip UWB antenna (UWBA). The proposed UWBA can work at eight modes (as shown in Table 1) using controlled switches (ON and OFF). There are three slots in the resonator; C-, L-, and U-shaped slots. The optical switches are made by placing $0.5 \times 0.5\ \mathrm{mm}^2$ silicon wafers over the slots of the resonator. When laser is applied to all switches (ON state) the notches disappear and the antenna operates in full UWB frequency range from 2.6 to 11.8 GHz. In case, all switches are OFF, all the three notches are activated.

A) Antenna design

Coplanar-fed microstrip UWB antenna was designed on a $35 \times 28\ \mathrm{mm}^2$ FR4 substrate with relative dielectric constant of 4.6 and thickness of 1.5 mm .This design proposes triple narrow notched bands at center frequencies 3.5 GHz "WiMAX", 5.5 GHz "WLAN" and 8.4 GHz "X-band satellite communication". The notched bands can be achieved by adjusting the dimensions of the microstrip structure and by inserting inverted C, L, and U-shaped slots. The coplanar-fed microstrip UWB antenna is shown in Fig. 2(a), while Fig. 2(b) illustrates the inserted optically controlled switches. The proposed UWBA can work at eight modes by controlling these switches (either ON or OFF states). The optical switches are made by placing $0.5 \times 0.5\ \mathrm{mm}^2$ silicon wafers over the slots of the resonator. When laser is applied to all switches (ON state) the notches disappear and the antenna operates in full UWB frequency range from 2.8 to 11.8 GHz. In case, all

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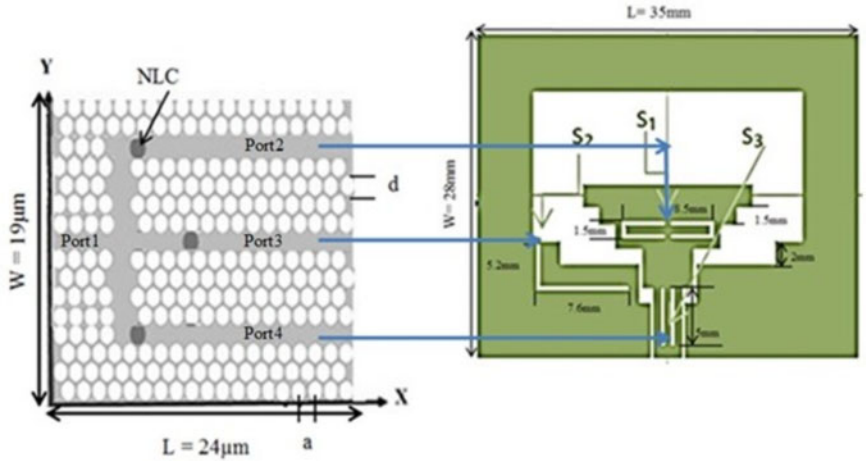


Fig. 1. The system of optically controlled UWB antenna using optical router.

switches are OFF, all the three notches are activated. Table 1 explains the eight modes of operation of the proposed antenna. The light was directed to the switches through reconfigurable optical router with the photonic crystal substrate [10], which has one input port and three output ports.

B) Optical reconfigurable router design

The reconfigurable optical router has one input port and three output ports.

The role of the reconfigurable optical router is to direct the light to the optical switches according to the required operating state. The proposed router is composed of three photonic crystal fibers (PCFs) waveguides. Each PCF wave guide has a cavity which is filled with nematic liquid crystal (NLC) of type E7. The NLC cavities permit the optical signal to propagate through the channel by changing the external bias. According to three biasing states of each of the three NLC cavities, the router has eight operating modes. In these operating modes, the router can transmit light from one port, two ports or three ports simultaneously or no light is transmitted at all. The switches that are embedded in the antenna determine the operating mode of the UWBA. The NLCs are anisotropic materials consisting of rod-like molecules. The alignment of the NLC molecules with rotation angle φ can be controlled using two electrodes. In the unbiased state, the NLC molecules are aligned along the x-axis with rotation angle $\varphi = 0^\circ$. However, in the biased state, the NLC molecules are oriented along the direction of the electric field in the z-direction with $\varphi = 90^\circ$ [10–12]. According to the biasing state of the cavity, the light is allowed or prohibited to propagate through the switch. In the unbiased state, no light propagates (OFF state). However, in the biased state the light can propagate through the switches (ON state).

Table 1. The different states of the reconfigurable antenna.

State	Notched band	S_1	S_2	S_3
1	3.5 & 5.5 & 8.5 GHz	OFF	OFF	OFF
2	None	ON	ON	ON
3	3.5 GHz	ON	OFF	ON
4	5.5 GHz	OFF	ON	ON
5	8.5 GHz	ON	ON	OFF
6	3.5 & 5.5 GHz	OFF	OFF	ON
7	3.5 & 8.5 GHz	ON	OFF	OFF
8	5.5 & 8.5 GHz	OFF	ON	OFF

The top view of the proposed router is shown in Fig. 1. The proposed design composed of an air-hole array etched in a high-dielectric constant substrate with $\varepsilon_r = 11.7$. Each hole has a diameter "d" of 1.2 µm. The holes are arranged in a triangular lattice structure with lattice constant "a" where $d/a = 0.97$. Three rows of air holes are removed from the lattice in the substrate to form a waveguide without scattering. In the front of each line, there is a hole of the same diameter "d", which is filled with NLC of type E7.

The parameters of the supposed photonic band gap (PBG) structure are chosen in order to realize the PBG effect (zero transmission) in a certain wavelength range [12–17].The transmission characteristics (S_{21}, S_{31}, and S_{41}) for this router are simulated using CST at wavelength $\lambda = 1.55$ µm and at the operating state 7 (switch S_1 is ON and switches S_2 and S_3 are OFF).The simulated values are $S_{21} = 0.884$, $S_{31} = 0.045$, and $S_{41} = 0.047$. This shows that the optical power loss in ON and OFF states are 2.2 and 4.7% respectively.

C) Photonic crystal fibers

PCFs are fibers with an internal periodic structure made of capillaries, filled with air, laid to form a certain lattice structure. Light can propagate along the fiber in defects of its crystal structure. A defect is realized by removing one or more central capillaries. PCFs are anew class of optical fiber-combining properties of optical fibers and photonic crystals. They possess a series of unique properties impossible to achieve in classical fibers. The design of PCFs is very flexible. There are several parameters to manipulate: lattice pitch, air-hole shape and diameter, refractive index of the glass, and type of lattice. Freedom of design allows one to obtain endlessly single-mode fibers, which are single mode in all optical range and a cut-off wavelength does not exist. Moreover, there are two guiding mechanisms in PCF: index guiding mechanism (similar to the one in classical optical fiber) and the PBG mechanism [18–21]. Photonic crystal substrates for high-speed THz applications are given in [22].

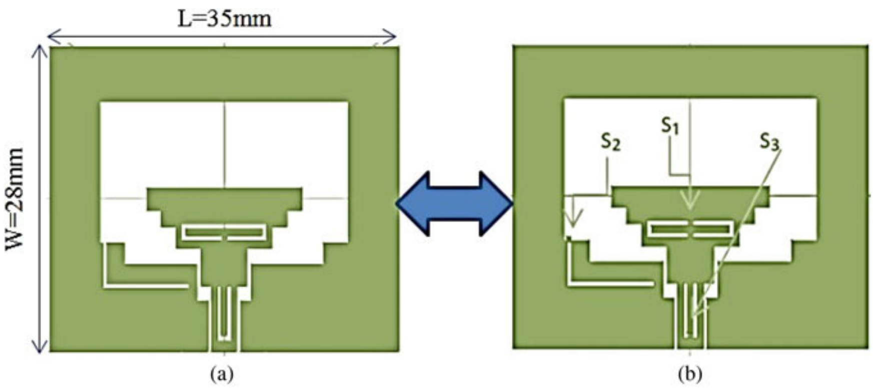


Fig. 2. The geometry of the proposed UWB antenna. (a) The original design. (b) UWB antenna without three switches.

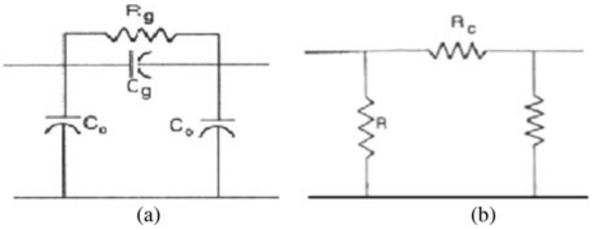


Fig. 3. Equivalent circuit of the switch (a) in the absence of laser and (b) with laser.

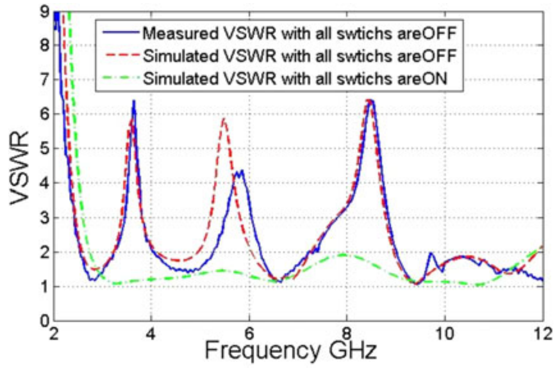


Fig. 4. VSWR of UWBA at “state1” and “state2”.

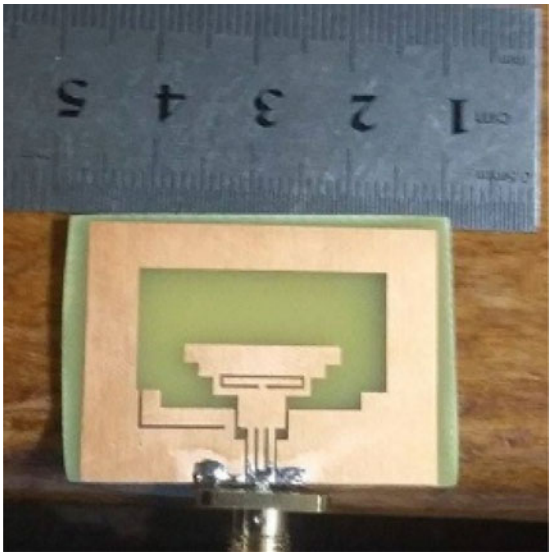


Fig. 5. Fabricated antenna.

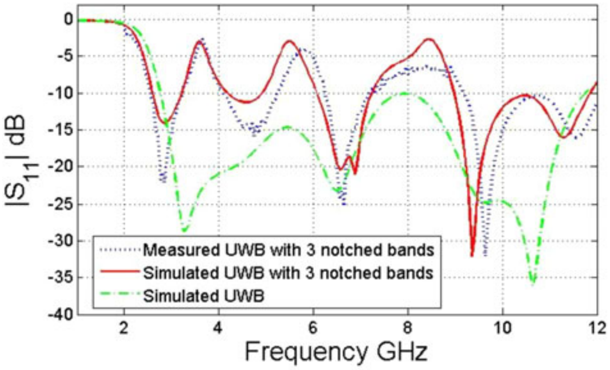


Fig. 6. Measured and simulated S_{11} for “states 1 and 2”.

D) The optical switch

The switches are formed by placing 0.5 × 0.5 mm² silicon wafers, having thickness $t = 0.5\ \mu m$ and $\varepsilon_r = 11.7$, over the slots of the resonator. The principle of operation of such an optically controlled switch has been studied in [6]. During the absence of the controlling optical signal, the model shown in Fig. 3(a) can represent the silicon wafer. The wafer conductance G_g, resistance R_g and capacitances C_g and C_o are evaluated using the equations in [6]. On the other hand, when the wafer area (0.5 × 0.5 mm²) is irradiated by uniform optical power, the switch-equivalent circuit is modeled as shown in Fig. 3(b). For uniform

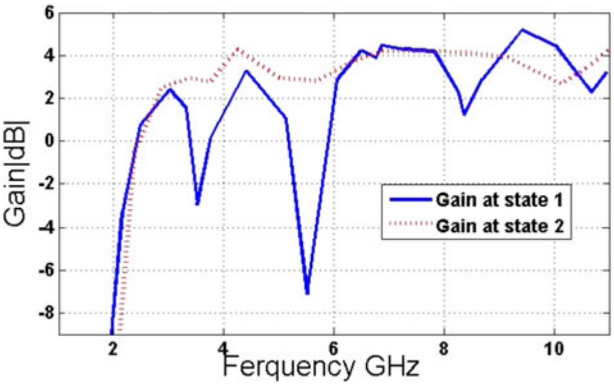
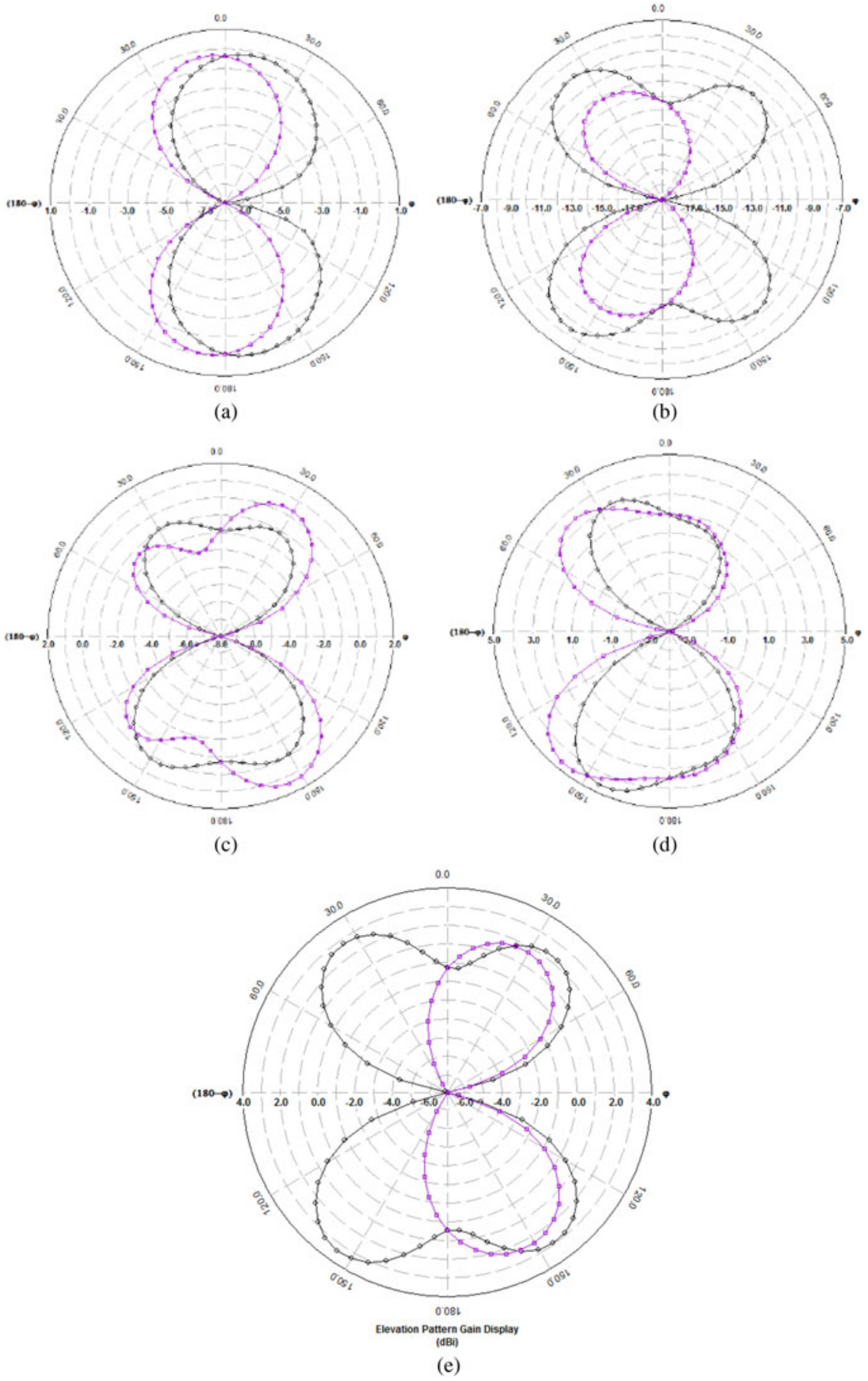


Fig. 7. UWB Antenna gain when all switches are either ON or OFF.

quasi-CW irradiation, and assuming linear recombination, the dynamic wafer resistances R and R_c are calculated according to formulas in [6]. Incident light generates free carriers in the silicon wafer (generated photoconductivity). The switching time depends on the effective carrier lifetime, which will depend on the excess carrier concentration, and the type of recombination process takes place. In this case, the effective carrier lifetime will be in the range from 10^{-12} to 10^{-15} s, which is suitable for fast communication systems [5, 6].

III. SIMULATION AND EXPERIMENTAL RESULTS

Figure 4 shows the simulated voltage standing wave ratio (VSWR) in two cases, when all switches are either OFF (state 1) or ON (state 2) as shown in Table 1. The bands with center frequencies 3.5, 5.5, and 8.5 GHz are rejected when all switches (S_1, S_2, and S_3) are OFF and consequently the UWB is divided into multiband at center frequencies 2.7, 4.7, 6.72, and 9.69 GHz. When all switches are ON, we obtain the UWB range from 2.6 to 11.8 GHz with return



(a) (b) (c) (d) (e)

Fig. 8. Radiation patterns at frequencies: (a) 3.55 GHz, (b) 5.5 GHz, (c) 8.425 GHz, (d) 9.69 GHz, and (e) 6.72 GHz.

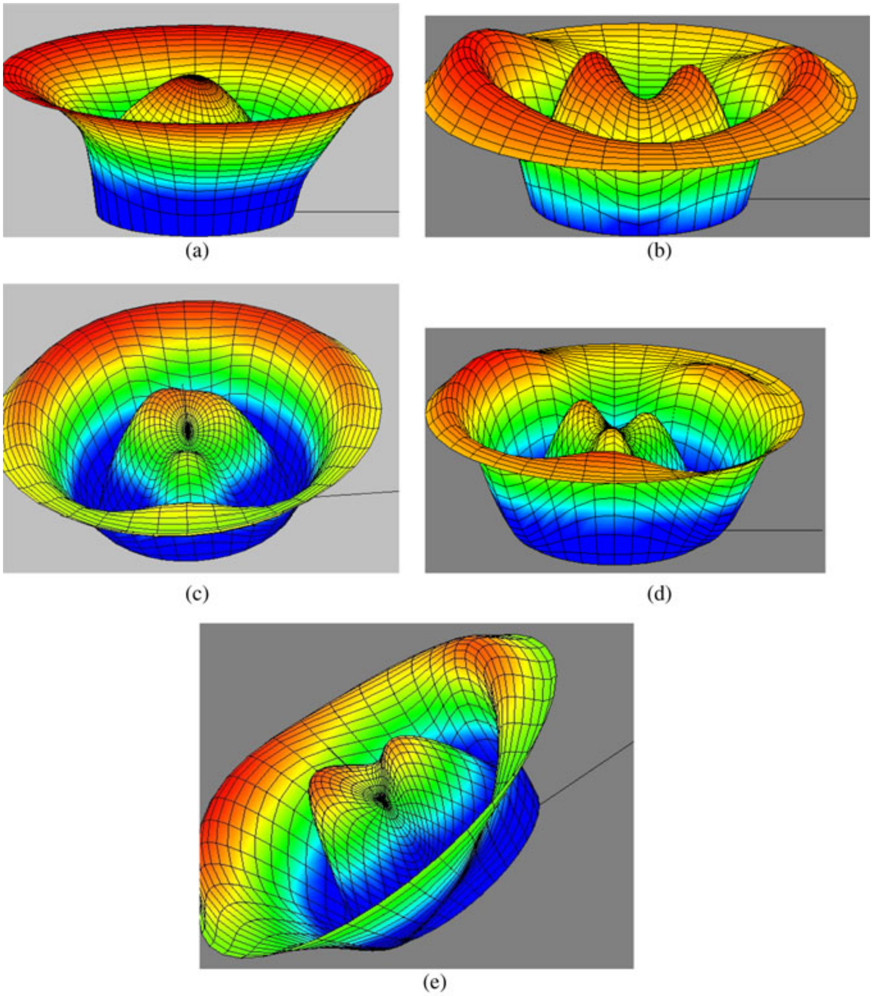


Fig. 9. 3D Radiation patterns at frequencies 3.475, 5.455, 8.425, 9.69, and 6.72 GHz.

loss less than −10 dB and VSWR of the whole UWB is <2. Figure 5 shows the fabricated antenna, while Fig. 6 presents comparison between measured and simulated return loss (S_{11}). A measurement of the antenna was performed in the anechoic chamber (using VNA-Rohde&Schwarz-ZVA67) and it fits well with CST & IE3D simulations. Moreover, the average gain of this antenna is 4.5 dBi (Fig. 7).

IV. RADIATION PATTERNS

The simulated *E*- and *H*-plane normalized radiation patterns at 3.55, 5.5, 8.425, 9.69, and 6.72 GHz for "state 1" are plotted in Fig. 8. Radiation patterns are semi-omni-directional. Three-dimensional (3D) radiation patterns are shown in Fig. 9.

V. CONCLUSIONS

An optically reconfigurable notched bands UWB antenna has been presented. The antenna was designed with etched C-, L-, and U-shaped slots and integrated silicon switches. The proposed antenna has tree optical switches, which can be turned ON or OFF according to the incident light. The incident light is coupled to the switches through an optical router. The reconfigurable optical router has three PCF waveguides with a NLC cavity at the entrance of each one. The router directs the light to the optical switches by changing the external bias of the NLC cavities. The proposed antenna yields an UWB that extends from 2.6 to 11.8 GHz with switchable single notched bands of 3.5, 4.5, or 8.5 GHz for WiMAX, WLAN, and other applications .The measured results of the proposed antenna well agree with the simulated ones. The antenna radiation patterns are almost omni-directional in the pass band ranges with quite satisfactory gain. This proposed design can work on eight modes, which are suitable for multimode, multiband, and UWB radio communications.

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