Microwave and Millimeter-Wave MIMO Antenna Using Conductive ITO Film

SO, Kwok Kan; CHEN, Bao-Jie; CHAN, Chi Hou

Published in:
IEEE Access

Published: 01/01/2020

Document Version:
Final Published version, also known as Publisher’s PDF, Publisher’s Final version or Version of Record

License:
CC BY

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1109/ACCESS.2020.3037900

Publication details:
SO, K. K., CHEN, B.-J., & CHAN, C. H. (2020). Microwave and Millimeter-Wave MIMO Antenna Using Conductive ITO Film. IEEE Access, 8, 207024-207033. Article 9259036. https://doi.org/10.1109/ACCESS.2020.3037900

Citing this paper
Please note that where the full-text provided on CityU Scholars is the Post-print version (also known as Accepted Author Manuscript, Peer-reviewed or Author Final version), it may differ from the Final Published version. When citing, ensure that you check and use the publisher's definitive version for pagination and other details.

General rights
Copyright for the publications made accessible via the CityU Scholars portal is retained by the author(s) and/or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights. Users may not further distribute the material or use it for any profit-making activity or commercial gain.

Publisher permission
Permission for previously published items are in accordance with publisher’s copyright policies sourced from the SHERPA RoMEO database. Links to full text versions (either Published or Post-print) are only available if corresponding publishers allow open access.

Take down policy
Contact lbscholars@cityu.edu.hk if you believe that this document breaches copyright and provide us with details. We will remove access to the work immediately and investigate your claim.
Microwave and Millimeter-Wave MIMO Antenna Using Conductive ITO Film

KWOK KAN SO1, (Senior Member, IEEE), BAO-JIE CHEN1, (Member, IEEE), AND CHI HOU CHAN2, (Fellow, IEEE)
1State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong, Hong Kong
2State Key Laboratory of Terahertz and Millimeter Waves, Department of Electrical Engineering, City University of Hong Kong, Hong Kong
Corresponding author: Kwok Kan So (eekksso@cityu.edu.hk)

This work was supported in part by the China Science and Technology Exchange Center, Ministry of Science and Technology, China, under Grant 2017/YFE190400.

ABSTRACT This paper will present a novel design of optically transparent multiple-input multiple-output (MIMO) antenna made by indium tin oxide (ITO) films. The MIMO antenna involves patch and monopole antenna elements at 4.9 GHz and 26 GHz respectively. The upper and lower surface of the MIMO antenna are covered by a thin film of glass substrate with conductive ITO coatings, while top layer is a radiating elements and the bottom layers are ground planes. Both patch and monopole antennas are fed by transparent 50Ω transmission lines. The prototypes were fabricated by an in-house photolithography process. Measurements are carried out to confirm the simulation. The characteristics showed that the proposed MIMO antenna can be considered as a potential antenna for 5G smartphone communications applications.

INDEX TERMS Multiple-input multiple-output, indium tin oxide, patch, monopole, glass, 5G, smartphone.

I. INTRODUCTION

While we are at the dawn of the fifth generation (5G) wireless communications, its higher data transmission speed and lower latency for real-time interaction open up new opportunities for users. This performance will not only provide new video formats like 360-degree video, but also enhance new technologies such as robotics, autonomous driving, augmented or virtual reality interaction, and a tactile internet applications ranging from industry automation and transport systems, while it may benefit emergency communication, healthcare, education and gaming in smart city. In order to provide wireless communication channels which is high speed, reliable and secure for mobile users, the antenna design for mobile phones have been a challenging topic to support the new 5G frequency bands. Two frequency ranges, sub-6GHz and millimeter-wave frequencies are the most concerned and recommended by related professionals enhanced mobile broadband. Multiple-input multiple-output (MIMO) antennas have been demonstrated [1]–[6] to achieve higher data rate for the sub-6 GHz operation. Over the past decade, conventional antennas are made by metal as a radiator, which are mounted on the printed circuit board (PCB) [1]–[12] substrate. Many designs have been demonstrated using substrates at lower relative permittivity [13]–[16]. Wider bandwidth and higher efficiency have been achieved at the expense of substrate thickness. In [17], [18], the use of magneto-dielectric material for antenna substrate has been proposed. Complex electric properties, relative permittivity and permeability with the dielectric loss tangent and magnetic loss tangent are characterized. Slot in metal frame mobile phone antennas [19]–[21] have been investigated. The capacitive coupling between the internal antenna and slot in metal frame can generate multiband antenna in the complex and heavy structures.

Recently, some researchers [22]–[26] have studied optical transparent antennas using a metal mesh structure which is placed on the transparent acrylic or glass for wireless applications. Unfortunately, the visible metal mesh structure is not suitable for mobile phone antenna-on-display (AoD). Highly transparent conductive indium tin oxide (ITO) [27]–[29] are investigated for mobile phone antenna. An ITO film is printed on the glass panel of smartphone to become an optically invisible AoD with the advantage of saving PCB and the proposed AoD is shown in Fig. 1.

In this paper, the proposed ITO MIMO antenna printed on a glass substrate, which is mimicking the display panel of a smartphone will be demonstrated for microwave
(from 4.8 GHz to 5 GHz) and millimeter-wave band (from 24.25 GHz to 27.5 GHz) simultaneously. Measurements have been carried out to verify the design. This paper will be presented as follows. Section II will describe ITO and glass characteristics in microwave band. Section III will introduce the geometry and provides the results of ITO patch, monopole, and MIMO antennas in microwave band. Section IV will present the ring resonator which has been studied for glass characteristic at 26 GHz, and Section IV will propose and present the performance of the geometry of an ITO patch and monopole antennas in millimeter-wave band, and a MIMO antenna with elements working in microwave and millimeter-wave band. Finally, a conclusion is given in Section V.

II. MATERIAL CHARACTERISTICS

A highly transparent conductive ITO supplied from Luoyang Guluo Glass Co., Ltd., China, was used as a conductive material for the proposed antenna. It is well known that thicker ITO film results in smaller sheet resistance, but lower optical transparency. For our designs, the transparency is about 84%. The sheet resistance, $R_s$, and thickness, $t$, of ITO transparent conductive films are $6 \Omega$/sq and 185 nm, respectively. The electrical conductivity, $\sigma \sim 9 \times 10^5$ S/m, was calculated based on

$$\sigma = \frac{1}{R_s \times t}$$  \hspace{1cm} (1)

An ITO film is coated on a 1.1 mm thick glass substrate with a relative permittivity, $\varepsilon_r$ of 5.5 and loss tangent, $\tan \delta$ of 0.001 in microwave band. The glass panel was also provided by Luoyang Guluo Glass Co., Ltd.

III. ITO ANTENNA IN MICROWAVE BAND

A. ITO PATCH ANTENNA

Fig. 2 (a) shows the perspective view of a transparent ITO patch antenna (Ant1). The resonant length of patch is $\sim \lambda_e/2$, where $\lambda_e$ is effective wavelength. The top and bottom layers are radiating square patch and ground plane (GND) with edge length of 12.8 mm and 30 mm, respectively. The patch is fed by a 50 $\Omega$ transmission line. Both conductive layers are realized by ITO transparent conductive films.

The radiation characteristics of Ant1 are simulated with High Frequency Structure Simulator (HFSS). The parameters of $\sigma = 9 \times 10^5$ S/m, $\varepsilon_r = 5.5$, and $\tan \delta = 0.001$ are used in the simulation. To verify the simulation results, a prototype of Ant1 at 4.9 GHz was fabricated by an in-house photolithography process. The ITO glass is covered with photoresist by spin coating. After baking, the photoresist is exposed to a pattern of intense UV light using a mask aligner, from SUSS MicroTec MA/BA 6. The exposed photoresist is then washed away by the developer solution, leaving windows of the bare underlying ITO film, which is then etched away by hydrochloric acid. Finally, the remaining photoresist is removed by acetone and the ITO pattern is formed after the etching process. Shown in Fig. 2 (b), a 3.5 mm jack Sub-Miniature version A (SMA) connector is used for measurement. Its reflection coefficient was measured by an Agilent PNA E8361A, whereas its antenna gain and radiation pattern were measured with a compact range antenna measurement system. Fig. 3 shows the measured and simulated reflection coefficients. It can be seen that Ant1 has a measured and simulated bandwidth of 4.3% (with reflection coefficient $\leq -10$ dB) from 4.798 GHz to 5.01 GHz. The measured and simulated gains are also shown in Fig. 3. The maximum measured and simulated gains are 2.3 dBi and 2.6 dBi at 4.9 GHz, respectively. Fig. 4 depicts the measured and simulated radiation patterns of Ant1 at 4.9 GHz. The radiation patterns have broadside, symmetrical, low cross-polarized level, and low back radiation in the $\phi = 0^\circ$ and $90^\circ$ planes within the entire operating band.
B. ITO MONOPOLE ANTENNA

Fig. 5 (a) shows the perspective view of a transparent ITO monopole antenna (Ant2). The resonant length of monopole is $\sim 0.4\lambda_e$. The top and bottom layers are a radiating square monopole with an edge length of 10.4 mm and a 30 mm $\times$ 8 mm rectangular GND, respectively. The monopole is fed by a 50 $\Omega$ transmission line.

The performances of Ant2 are simulated with HFSS, a prototype was fabricated as shown in Fig. 5 (b). Fig. 6 shows the measured and simulated reflection coefficients of Ant2, it achieves a wide impedance bandwidth. The measured and simulated gains are also shown in Fig. 6, which have an average gain of 2.2 dBi at $\theta = 60^\circ$ over the entire bandwidth. Fig. 7 displays the measured and simulated radiation patterns of Ant2 at 4.9 GHz. The co-polarized fields in $\phi = 0^\circ$ and $90^\circ$ planes are bi-directional and omni-directional, respectively, which are also symmetrical. The cross-polarized field at $\phi = 90^\circ$ plane is a four-leaf clover shaped pattern and the difference between co-polarized and cross-polarized levels is larger than 15 dB.

C. ITO MIMO ANTENNA

Parametric study is carried out for the separation between Ant1 and Ant2 using HFSS on a rectangular glass substrate with length 150 mm and width 70 mm which is the size of a typical smartphone display. Fig. 8 shows the top view of transparent ITO MIMO antenna (Ant1 and Ant2). The patch and monopole are on the top of the glass while the antenna GNDs are at the bottom of the glass.

The S-parameter and gains of transparent ITO MIMO antenna are studied in three cases. For Case 1, the position of Ant2 remains unchanged and the distance between Ant1 and Ant2, $d_1$ is varied along y direction and vice versa for Case 2. For Case 3, the positions of Ant1 and Ant2 are...
changed simultaneously by reducing $d_1$. **Ant1** and **Ant2** are denoted as Port 1 and Port 2, respectively. Fig. 9 illustrates $S_{12}$ and **Ant2** gain against $d_1/\lambda_0$. $S_{12}$ decreases from $-23$ dB to $-36$ dB and **Ant2** gain increases from $-11.78$ dBi to $1.28$ dBi monotonically with $d_1$ for the three cases, respectively. The lowest $S_{12}$ and highest **Ant2** gain are obtained when $d_1/\lambda_0 = 1.47$ at $f_0 = 4.9$ GHz and the structure is shown in Fig. 8. It is noted that $S_{11}$, $S_{22}$, and **Ant1** gain are stable when moving **Ant1** or/and **Ant2** for the three cases and the results are omitted in Fig. 9.

A prototype of transparent ITO MIMO antenna with two antennas was fabricated as shown in Fig. 10. Fig. 11 shows the measured and simulated $S$-parameters of the transparent ITO MIMO antenna. Similar responses of $S_{11}$ and $S_{22}$ are obtained when comparing to each single element. It can be seen that **Ant1** has a measured bandwidth of 5.6% (with $S_{11} \leq -10$ dB) from 4.776 GHz to 5.052 GHz. **Ant2** also achieves a wide impedance bandwidth (with $S_{22} \leq -10$ dB) across the entire operating band. Good measured isolation between two ports below $S_{12} = -32$ dB is obtained. The measured and simulated gains are shown in Fig. 12, both **Ant1** and **Ant2** measured gains have 1 dBi for both ports at 4.9 GHz. Fig. 13 displays the measured and simulated radiation patterns of **Ant1** and **Ant2**. The broadside and low back radiation are obtained in Fig. 13 (a) and co-polarized field in $\phi = 90^\circ$ plane has 1 dBi at $\theta = 60^\circ$ in Fig. 13 (b).

**IV. ITO ANTENNA IN MICROWAVE AND MILLIMETER-WAVE BAND**

In the previous section, it has been successfully demonstrated that applying ITO patch and monopole antennas...
for MIMO operation at microwave band (from 4.8 GHz to 5GHz). In this section, the ITO MIMO antenna is applied in microwave (from 4.8 GHz to 5GHz) and millimeter-wave (from 24.25 GHz to 27.5 GHz) bands design.

A. MILLIMETER-WAVE CHARACTERIZATION OF GLASS SUBSTRATE

The dielectric characteristics of glass substrate are studied in millimeter-wave band. The most precise methods for determining characteristics of the substrate are the resonator-based methods, including parallel-plate resonators, microstrip ring resonators, and cavity resonators. The parallel-plate resonator method is usually applied in the microwave band. For millimeter-wave band, the microstrip ring resonator method is investigated for the dielectric characteristics of the glass substrate.

Fig. 14 shows the prototype of a transparent ITO ring resonator with frequency resonance at 26 GHz and is shown in Fig. 14. A peak position and −3dB bandwidth at the resonant frequency from measured $S_{21}$ are used to calculate $\varepsilon_r$ and $\tan \delta$ from equations (2) to (8).

\[
\varepsilon_r = \frac{2 \times \varepsilon_{\text{eff}} + M - 1}{M + 1} \tag{2}
\]

\[
\varepsilon_{\text{eff}} = \left( \frac{c}{2 \times \pi \times r_m \times f_0} \right)^2 \tag{3}
\]

\[
M = \left( 1 + \frac{12 \times h}{w_{\text{eff}}} \right)^2 \tag{4}
\]

$w_{\text{eff}}$ in (4) is the effective ITO ring width and is given as follows:

\[
w_{\text{eff}} = w + \frac{1.25 \times t}{\pi} \left[ 1 + \ln \left( \frac{2h}{t} \right) \right] \tag{5}\]

where $w$ is the width of the ITO ring.

The loss tangent is computed using (6) as follows:

\[
\tan \delta = \frac{\alpha \times \lambda_0 \times \sqrt{\varepsilon_{\text{eff}} \left( \varepsilon_r - 1 \right)}}{8.686 \times \pi \times \varepsilon_r \left( \varepsilon_{\text{eff}} - 1 \right)} \tag{6}
\]
TABLE 1. Ring dimensions, measured parameters from $S_{21}$, and calculated dielectric characteristics at 26 GHz.

| Parameters | $r_m$ (mm) | $w$ (mm) | $f_s$ (GHz) | BW_{-3dB} (GHz) | $L_A$ (dB) | $\varepsilon_r$ | tan $\delta$ |
|------------|------------|----------|-------------|-----------------|---------|---------------|--------------|
| Values     | 0.965      | 0.5      | 26          | 0.72            | 36.21   | 5.4           | 0.0035       |

where $\lambda_0$ is the free-space wavelength and the attenuation, $\alpha$ is obtained from its unloaded quality factor, $Q_0$ given in (7).

$$\alpha = \frac{\pi}{Q_0 \lambda_{\text{eff}}} \quad (7)$$

where $\lambda_{\text{eff}}$ is the effective wavelength and $Q_0$ is obtained from the insertion loss, $L_A$ and the $-3$dB bandwidth, BW_{-3dB} measured at $f_0$ using (8) below:

$$Q_0 = \frac{f_0}{BW_{-3dB} \times \left(1 - 10^{-\frac{L_A}{20}}\right)} \quad (8)$$

Designed ring dimensions, measured parameters from $S_{21}$, and calculated dielectric characteristics are listed in Table 1.

**B. MILLIMETER-WAVE ITO PATCH ANTENNA**

Fig. 15 (a) shows the perspective view of a transparent ITO patch antenna (Ant3) at 26 GHz. The top and bottom layers of Ant3 are radiating square patch and GND with an edge length of 2.2 mm and 10 mm, respectively. The radiation characteristics of Ant3 are simulated with HFSS using $\varepsilon_r = 5.4$ and tan $\delta = 0.0035$ of glass substrate.

A prototype of Ant3, shown in Fig. 15 (b), was fabricated with a 2.92 mm jack SMA connector. Fig. 16 shows the measured and simulated reflection coefficients. It can be seen
that Ant3 has measured and simulated bandwidths of 22% from 22.7 GHz to 28.3 GHz and 25% from 22.2 GHz to 28.55 GHz, respectively. The measured and simulated gains of Ant3 are 3.9 dBi and 4.4 dBi at 26 GHz, respectively, as shown in Fig. 16. Fig. 17 depicts the measured and simulated radiation patterns of Ant3 at 26 GHz. The broadside radiation patterns are obtained within the entire operating band.

C. MILLIMETER-WAVE ITO MONOPOLE ANTENNA

Fig. 18 (a) shows the perspective view of a transparent ITO square monopole antenna (Ant4) at 26 GHz. The top and bottom layers of Ant4 are a radiating square monopole with an edge length of 1.9 mm and a 10 mm × 3.2 mm rectangular GND, respectively. The radiation characteristics of Ant4 are simulated with HFSS using $\varepsilon_r = 5.4$ and $\tan \delta = 0.0035$ of glass substrate.

A prototype of Ant4, shown in Fig. 18 (b), was fabricated with a 2.92 mm jack SMA connector. Fig. 19 shows the measured and simulated reflection coefficients of Ant4 and it achieves a wide impedance bandwidth. The measured and simulated gains of Ant4 are also shown in Fig. 19, which have measured and simulated gains of 3.7 dBi and 4.2 dBi at $\theta = 80^\circ$ and 26 GHz. Fig. 20 displays the measured and simulated radiation patterns of Ant4 at 26 GHz. The co-polarized fields in $\phi = 90^\circ$ plane is conical and symmetrical.

D. MICROWAVE AND MILLIMETER-WAVE ITO MIMO ANTENNA

Fig. 21 shows the top view of a transparent ITO MIMO antenna (Ant1, Ant2, Ant3, and Ant4). The patches...
operating at 4.9 GHz (Ant1), 26 GHz (Ant3) and monopoles operating at 4.9 GHz (Ant2), 26 GHz (Ant4) are on the top of the glass while the GNDs of the patch and monopole antennas are at the bottom of the glass. Parametric study is performed for the separation, $d_2$ between Ant3 and Ant4.

The S-parameters and gains of transparent ITO MIMO antenna are studied in three cases. For Case 1, the position of Ant4 remains unchanged and distance between Ant3 and Ant4, $d_2$ is varied along y direction and vice versa for Case 2. For Case 3, the positions of Ant3 and Ant4 are changed simultaneously by reducing $d_2$. The feeds of Ant1, Ant2, Ant3, and Ant4 are denoted as Ports 1, 2, 3, and 4, respectively. Fig. 22 demonstrates $S_{34}$ and Ant4 gain against $d_2/\lambda_0$. In general, $S_{34}$ decreases from $-20$ dB to $-46$ dB and Ant4 gain increases from $-10.2$ dBi to $2.4$ dBi with $d_2/\lambda_0$ for the three cases, respectively. The lowest $S_{34}$ and the highest Ant4 gain are obtained when $d_2/\lambda_0 = 11.27$ at $f_0 = 26$ GHz and the structure is shown in Fig. 21. It is noted that other S-parameters and gains are stable when moving the Ant3 or/and Ant4 for the three cases and the results are omitted in the Fig. 22.

A prototype of the transparent ITO MIMO antenna with four antennas was fabricated. Two pieces of 3.5 jack and two pieces of 2.92 jack SMA connectors are used for measurement and are shown in Fig. 23. Fig. 24 shows the measured and simulated S-parameters of transparent ITO MIMO antenna with four antennas. Similar responses of $S_{11}$, $S_{22}$, $S_{33}$, and $S_{44}$ are obtained when comparing to the responses of each single element. From Fig. 24 (a) and (c), Ant1 and Ant3 have a measured bandwidth of 5.1% from 4.788 GHz to 5.038 GHz and 22% from 22.59 GHz to 28.32 GHz, respectively. Shown in Fig. 24 (b) and (d), Ant2 and Ant4 also achieve a wide impedance bandwidth across the entire operating band. $S_{12}$ and $S_{34}$ are equal to $S_{21}$ in Fig. 24 (a) and $S_{43}$ in Fig. 24 (c), respectively, and $S_{12}$ and $S_{34}$ are omitted in Fig. 24 (b) and 24 (d), respectively. Measured isolation between all ports are below $-35$ dB. The measured and simulated gains for four antennas are shown in Fig. 25.

The measured antenna gains at 4.9 GHz in Fig. 25 (a) and 26 GHz in Fig. 25 (b) are around 1 dBi and 2 dBi, respectively. Fig. 26 displays the measured and simulated radiation patterns of Ant1, Ant2, Ant3, and Ant4. Broadside and low back radiation patterns are obtained in Fig. 26 (a) and (c). The co-polarized field in $\phi = 90^\circ$ plane of Fig. 26 (b) and (d) are 1 dBi and 2 dBi at $\theta = 60^\circ$ and $80^\circ$, respectively. Finally, Table 2 lists the radiation characteristics of proposed and referenced [27] and [28] antennas reported ITO antennas.
This paper has studied the patch and monopole locating on the display, and then the broadside and conical radiation patterns can be obtained. References [27] and [28] are fed by probe with Rogers RT5880 and fed by microstrip line with stack patch, respectively. Although the gain is only 2 dBi, a simple structure with stripline feed method in the proposed one. It is noted that this is the first paper for demonstrating in ITO antenna at the microwave and millimeter-wave bands.

V. CONCLUSION

A novel design of optically transparent MIMO antenna made of conductive ITO films for microwave and millimeter-wave band is proposed. The single element of ITO patch and monopole antennas at 4.9 and 26 GHz are studied. The ITO MIMO antenna with two (4.9 GHz) and four elements (4.9 and 26 GHz) printed on the 150 mm × 70 mm rectangular glass substrate is investigated. The prototypes were fabricated by an in-house photolithography process. Measured results agree with the simulated results very well. The proposed MIMO antenna has potential applications in 5G smartphone.

ACKNOWLEDGMENT

The authors would like to thank the reviewers for their constructive comments. They are also grateful to Ms. Wing Chi Mok, Mr. Man Shing Leung, and Ms. Ching See Ip for their technical assistance.

REFERENCES

[1] A. A. Al-Hadi, J. Ilvonen, R. Valkonen, and V. Viikari, “Eight-element antenna array for diversity and MIMO mobile terminal in LTE 3500 MHz band,” Microwave Opt. Technol. Lett., vol. 56, no. 6, pp. 1323–1327, Jun. 2014.

[2] Z. Qin, M. Zhang, J. Wang, and W. Geyi, “Printed eight-element MIMO system for compact and thin 5G mobile handset,” Electron. Lett., vol. 52, no. 6, pp. 416–418, Mar. 2016.

[3] H. Xu, H. Zhou, S. Gao, H. Wang, and Y. Cheng, “Multimode decoupling technique with independent tuning characteristic for mobile terminals,” IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 7673–7675, Dec. 2017.

[4] I. R. R. Barani and K.-L. Wong, “Integrated inverted-F and open-slot antennas in the metal-framed smartphone for 2 × 2 LTE LB and 4 × 4 LTE M/HB MIMO operations,” IEEE Trans. Antennas Propag., vol. 66, no. 10, pp. 5004–5012, Oct. 2018.

[5] A. Zhao and Z. Ren, “Wideband MIMO antenna systems based on coupled-loop antenna for 5G N77/N87/N79 applications in mobile terminals,” IEEE Access, vol. 7, pp. 93761–93771, Jul. 2019.

[6] L. Cui, J. Guo, Y. Liu, and C.-Y.-D. Sim, “An 8-element dual-band MIMO antenna with decoupling stub for 5G smartphone applications,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 10, pp. 2095–2099, Oct. 2019.

[7] J. Ma, Y. Z. Yin, J. L. Guo, and Y. H. Huang, “Miniature printed octoband monopole antenna for mobile phones,” IEEE Antennas Wireless Propag. Lett., vol. 9, pp. 1033–1036, 2010.

[8] S. Wang, H. W. Lai, K. K. So, K. B. Ng, Q. Xue, and G. Liao, “Wide-band shorted patch antenna with a modified half U-slot,” IEEE Antennas Wireless Propag. Lett., vol. 11, pp. 689–692, 2012.

[9] N. Takemura, “Tunable inverted-L antenna with split-ring resonator structure for mobile phones,” IEEE Trans. Antennas Propag., vol. 61, no. 4, pp. 1891–1897, Apr. 2013.

[10] K.-L. Wong and C.-Y. Huang, “Triple-wideband open-slot antenna for the LTE metal-framed tablet device,” IEEE Trans. Antennas Propag., vol. 63, no. 12, pp. 5966–5971, Dec. 2015.

[11] M. Stanley, Y. Huang, H. Wang, H. Zhou, Z. Tian, and Q. Xu, “A novel reconfigurable metal rim integrated open slot antenna for octa-band smartphone applications,” IEEE Trans. Antennas Propag., vol. 65, no. 7, pp. 3352–3363, Jul. 2017.

[12] P. Qi and Q. Feng, “Low-profile compact antenna for octa-band metal-rimmed mobile phone applications,” IEEE Trans. Antennas Propag., vol. 68, no. 1, pp. 54–61, Jan. 2020.

[13] B.-N. Kim, S.-O. Park, J.-K. Oh, and G.-Y. Koo, “Wideband built-in antenna with new crossed C-shaped coupling feed for future mobile phone application,” IEEE Antennas Wireless Propag. Lett., vol. 9, pp. 572–575, 2010.

[14] Q. Guo, R. Mittra, F. Lei, Z. Li, J. Ju, and J. Byun, “Interaction between internal antenna and external antenna of mobile phone and hand effect,” IEEE Trans. Antennas Propag., vol. 61, no. 2, pp. 862–870, Feb. 2013.

[15] K. Ishimiya, C.-Y. Chiu, and J.-I. Takada, “Multiband loop handset antenna with less ground clearance,” IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 1444–1447, 2013.

[16] H. Wang, Y. Wang, J. Wu, P. Chen, Z. Wu, C.-Y.-D. Sim, and G. Yang, “Small-size reconfigurable loop antenna for mobile phone applications,” IEEE Access, vol. 4, pp. 5179–5186, Sep. 2016.

[17] S. Bae, Y.-K. Hong, J.-J. Lee, W.-M. Seong, J.-S. Kam, W.-K. Ahn, S.-H. Park, G. S. Abo, J. Jalli, and J.-H. Park, “Miniaturized broadband ferite T-DMB antenna for mobile-phonpe applications,” IEEE Trans. Magn., vol. 46, no. 6, pp. 2361–2364, Jun. 2010.

[18] J. Lee, J. Lee, K. Min, and Y. Cheon, “Miniaturized antennas with reduced hand effects in mobile phones using magneto-dielectric material,” IEEE Antennas Wireless Propag. Lett., vol. 13, pp. 935–938, 2014.

[19] J. Kurvinen, A. Lehtovuori, J. Mai, C. Wang, and V. Viikari, “Metal-covered handset with LTE MIMO, Wi-Fi MIMO, and GPS antennas,” Prog. Electromagn. Res. C, vol. 80, pp. 89–101, Jan. 2018.

[20] D. Huang, Z. Du, and Y. Wang, “Compact antenna for 4G/5G metal frame mobile phone applications using a tuning line,” Electronics, vol. 17, no. 12, pp. 1–9, Dec. 2018.

[21] P. Yang, “Reconfigurable 3-D slot antenna design for 4G and sub-6G smartphones with metallic casing,” Electronics, vol. 9, no. 2, p. 216, Jan. 2020.

[22] S. H. Kang and C. W. Jung, “Transparent patch antenna using metal mesh,” IEEE Trans. Antennas Propag., vol. 66, no. 4, pp. 2095–2100, Apr. 2018.

[23] S. K. Podilchak, D. Comite, B. K. Montgomery, Y. Li, V. G.-G. Buendia, and Y. M. M. Antar, “Solar-panel integrated circularly polarized meshed patch for CubeSats and other small satellites,” IEEE Access, vol. 7, pp. 96560–96566, Aug. 2019.

[24] C. Ding, L. Liu, and K.-M. Luk, “An optically transparent dual-polarized stacked patch antenna with metal-mesh films,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 10, pp. 1981–1985, Oct. 2019.

[25] R. Yazdani, M. Yousefi, H. Alakbarian, H. Oraizi, and G. A. E. Vandenbosch, “Miniaturized triple-band highly transparent antenna,” IEEE Trans. Antennas Propag., vol. 68, no. 2, pp. 712–718, Feb. 2020.

[26] B. Xi, X. Liang, Q. Chen, K. Wang, J. Geng, and R. Jin, “Optical transparent antenna array integrated with solar cell,” IEEE Antennas Wireless Propag. Lett., vol. 19, no. 3, pp. 457–461, Mar. 2020.

[27] M. Stanley, Y. Huang, H. Zhou, A. Alieidin, and S. Joseph, “A transparent dual-polarized antenna array for 5G smartphone applications,” in Proc. IEEE Int. Symp. Antennas Propag., USNC/URSI Nat. Radio Sci. Meeting, Boston, MA, USA, Jul. 2018, pp. 635–636.

[28] Z. Yang, “A transparent dual-band dual-polarized mm-Wave antenna array for 5G smartphone application,” in Proc. Int. Symp. Antennas Propag., Xi’an, China, Oct. 2019, pp. 1–3.

[29] K. K. So, B. J. Chen, C. H. Chan, and K. M. Luk, “Study of MIMO antenna made of transparent conductive ITO films,” in Proc. IEEE Asia-Pacific Microw. Conf. (APMC), Singapore, Dec. 2019, pp. 515–517.

[30] L. Yang, A. Rida, R. Vyas, and M. M. Tentzeris, “RFID tag and RF structures on a paper substrate using inkjet-printing technology,” IEEE Trans. Microwave Theory Techn., vol. 55, no. 12, pp. 2894–2901, Dec. 2007.
KWOK KAN SO (Senior Member, IEEE) received the B.Eng. and Ph.D. degrees in electronic engineering from the City University of Hong Kong, Hong Kong, in 1999 and 2005, respectively. He joined the Wireless Communications Research Center, City University of Hong Kong, as an Assistant Engineer, in 2006. He is currently an Engineer with the State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong. His current research interests include dielectric resonator antennas, global positioning system antennas, small antennas, transparent antennas, millimeter-wave antennas, terahertz antennas, antenna arrays, and computational electromagnetics. Dr. So was a recipient of the Best Student Paper Award at the category of Microwave Theory and Techniques (MTT)/Antennas and Propagation (AP), the IEEE Hong Kong Section Joint Chapter on MTT/AP/LEOS 2000 in Hong Kong, and the Best Paper Award at the International Symposium on Antennas and Propagation (ISAP) 2008 in Taipei, Taiwan. He was the Technical Program Vice Chairman of the ISAP 2010, the Local Arrangement Chair of the 2011 IEEE International Workshop on Antenna Technology, the Publication Chair of the 2013 IEEE International Workshop on Electromagnetics (iWEM), the 2015 IEEE International Conference on Computational Electromagnetics, 2017 10th Global Symposium on Millimeter-Waves, and iWEM 2017. He is the Finance Chair of the 2020 Asia-Pacific Microwave Conference. From 2012 to 2014, he was the Secretary of the IEEE Hong Kong Section AP/MTT Joint Chapter. From 2015 to 2016, he was the Treasurer of the Chapter and the Chapter won the IEEE AP-S Best Chapter Award in 2016. He was the Vice-Chairman of the Chapter on 2017. From 2018 to 2019, he was the Chairman of the Chapter and the Chapter won the IEEE AP-S third place Best Chapter Award.

BAO-JIE CHEN (Member, IEEE) was born in Liaoning, China, in 1984. He received the B.S. and M.S. degrees in material science from Dalian Polytechnic University, Dalian, China, in 2007 and 2010, respectively, and the Ph.D. degree in electronic engineering from the City University of Hong Kong, Hong Kong, in 2014. He is currently an Engineer with the State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong. His current research interests include rare-earth-doped materials, optical amplifiers, and the development of terahertz devices and components.

CHI HOU CHAN (Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering from the Ohio State University, Columbus, OH, USA, in 1981 and 1982, respectively, and the Ph.D. degree in electrical engineering from the University of Illinois, Urbana, IL, USA, in 1987. From 1987 to 1989, he was a Visiting Assistant Professor with the Department of Electrical and Computer Engineering, University of Illinois. He joined the Department of Electrical Engineering, University of Washington, Seattle, WA, USA, in 1989, and was promoted to Associate Professor with tenure in 1993. In 1996, he joined the Department of Electronic Engineering, City University of Hong Kong (CityU), as a Professor, and was promoted to Chair Professor of Electronic Engineering in 1998. From 1998 to 2009, he was first the Associate Dean and then the Dean of the College of Science and Engineering, CityU, where he also served as an Acting Provost from July 2009 to September 2010. He is currently the Director of the State Key Laboratory of Terahertz and Millimeter Waves, CityU. His current research interests include computational electromagnetics, millimeter-wave circuits and antennas, and terahertz science and technology. Prof. Chan was elected as a Fellow of the IEEE in 2002, with the citation of “For Contributions to Computational Electromagnetics.” He received the 2019 IEEE Antennas and Propagation Society Harrington-Mittra Computational Electromagnetics Award for his fundamental contributions to fast solutions of integral equations using FFT with applications to scattering, antennas, and interconnect structures in homogeneous and layered medium. He is also bestowed with the 2019 Distinguished Alumni Award from the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign.

B * *