Design Evolution of Millimeter-wave Antenna-on-Display (AoD) on the TFE of an OLED Display for 5G and 6G

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Abstract

This paper presents the design evolution of millimeter-wave antenna-on-display (AoD) on the thin-film encapsulation (TFE) of an organic light-emitting diode (OLED) display for the 5th generation mobile communications (5G) and 6G applications. The reviewed evolution discusses the three leading designs (with the key design techniques and corresponding main performance) of the on-TFE millimeter-wave AoD for single-band coverage, dual-band coverage, and wideband coverage, systematically benefiting and effectively inspiring future AoD advances.

Author Keywords

5G; 6G; antennas; AoD; displays; millimeter-wave; OLED.

1. Introduction

AoD [1]–[9] is an innovative and emerging antenna technology generally achieved by inserting a visually transparent thin visually transparent film carrying visually transparent antenna(s) (typically formed by fine metal meshes) onto a display (and under the display's cover glass) as shown in Figure 1(a) [7]. AoD's three main advantages go as follows [1]: (1) the effective mitigation on the severe conflicts between more antennas and higher screen-to-body ratios for wireless mobile devices (especially smartphones, smart watches, etc.), (2) lower possibility of blockage (by hands or metal objects, e.g., metal tables) on the antennas in wireless mobile devices; (3) the good complement to the antenna-in-package (AiP) [10],[11] solution (the current mainstream solution for millimwter-wave antennas especially in wireless mobile devices) to enable overall broader spatial coverage of wireless signals. However, in addition to causing more complex manufacturing processes, higher costs, and thicker display modules, the mainstream add-on solution [3]–[6] for AoD usually leads to negative impacts, such as the Moiré effect, haze effect, degraded optical transparentcy, etc., to optical performance, too. Because the optical performance normally is the performance's first priority of a display (especially for smartphones, smart watches, smart glasses, VR/AR headsets, and so on), the AoD technology may not be widely applied if perceptible deterioration happens to display's optical performance. In view of the above issues, AoD designs on the TFE, especially of an OLED display, thus are proposed [7]–[9] by the authors.

According to the 3rd generation partnership project (3GPP) [12], for 5G (and for even 6G), the millimeter-wave bands are embraced in the whole frequency spectrum. To realize stronger wireless communication capabilities and better user experience in wireless communications, typically, multiple bands need to be supported. For the presented on-TFE millimeter-wave AoD [7]–[9] with single-band, dual-band, and wideband coverage, the key design techniques and systematic evoluton philosophy are clearly exhibited and discussed to inspire and trigger future AoD (including the on-TFE type and the add-on type) developments.

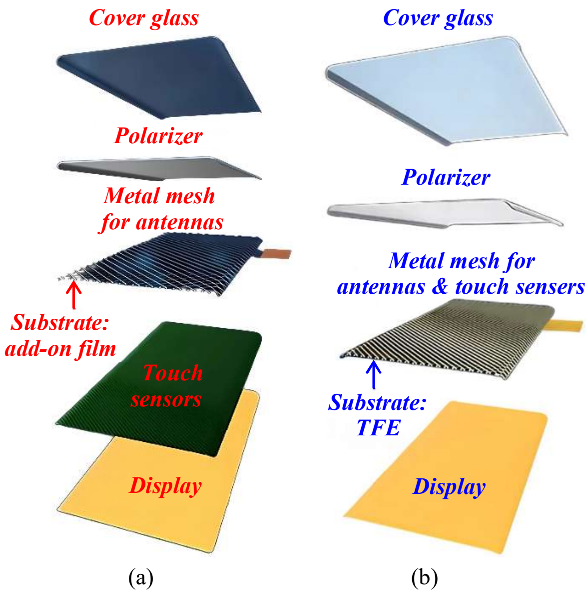

Figure 1. (a) Add-on AoD solution; (b) on-TFE AoD solution.

2. AoD on the TFE of an OLED

In Figure 1(b), the major stack-up of the on-TFE AoD solution is shown and compared with the mainstream add-on solution. For the on-TFE solution, the metal mesh for antennas is formed on the TFE (with the typical thickness less than 15 μm) of a display (especially an OLED one) by sputtering and etching and can be well shared with touch sensors as a co-layer integrated design. To put it differently, fot the on-TFE AoD solution, an additional inserted film as the substrate for metal-meshed antennas in the mainstream add-on solution consequently is not needed. Besides, the on-TFE metal mesh is designed to fully expose OLED pixels so that the optical performance of the on-TFE AoD solution can be much better secured than that of the add-on AoD solution, which is pivotal to AoD's popular applications. Furthermore, due to the elimination of the additional inserted thin film (and its corresponding adhesive) in the add-on AoD solution, the on-TFE AoD solution can reduce the manufacturing complexity and costs, and display module thicknesses as well.

3. On-TFE AoD Designs and Main Performance

3.1 *Single-band Millimeter-wave AoD*

As shown in Figure 2(a), an on-TFE single-band millimeter-wave AoD was proposed [7]. The metal-mesh AoD radiator is in a rectangular shape with a gap to get separated from the rest mesh for

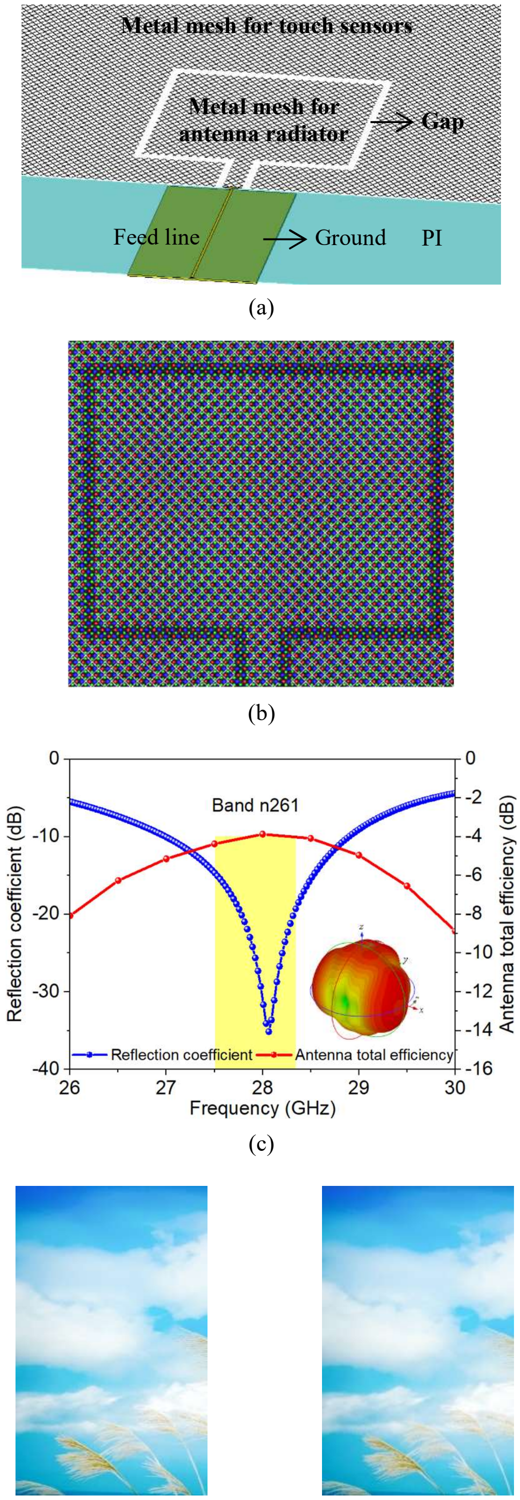

Figure 2. On-TFE single-band millimeter-wave AoD [7]: (a) structure, (b) OLED-pixels-exposed metal mesh, (c) reflection coefficient, antenna total efficiency, and 3-D realized gain pattern at 28.0 GHz. Images: (d) without and (e) with the on-TFE metal mesh.

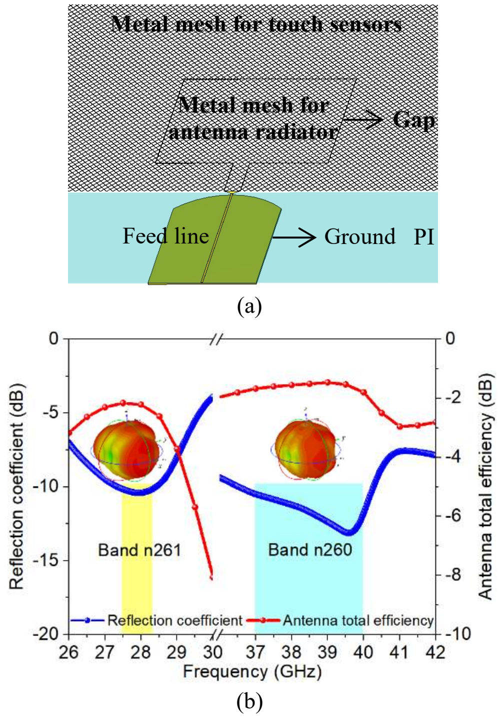

Figure 3. On-TFE dual-band millimeter-wave AoD [8]: (a) structure; (b) reflection coefficient, antenna total efficiency, and 3-D realized gain patterns at 28.0 GHz and 39.0 GHz.

co-layer touch sensors. The reference ground of the 50-Ω feed line (with polyimide (PI) as the substrate) is in a rectangular shape, too. Moreover, the designed OLED-pixels-exposed metal mesh is shown in Figure 2(b) where the red, blue, and green dots are the OLED subpixels. The corresponding main performance (i.e., the reflection coefficient, antenna total efficiency, and 3-D realized gain pattern at 28.0 GHz) of the designed single-band millimeter-wave AoD is shown in Figure 2(c). In terms of the well-recognized thereshold of –10 dB for the reflection coefficient, the frequency range from 26.98 GHz to 28.89 GHz can be embraced so that the prevailing 3GPP 5G millimeter-wave band n261 (27.50–28.35 GHz) hence can be supported by this AoD. Also, the in-band antenna total efficiency (including the feed-line loss) is higher than –3.86 dB, and the peak realized gain at 28.0 GHz (i.e., around the center freqyuecy of the band n261) is –0.35 dBi. The images without and with the on-TFE metal mesh for antennas and touch sensors are shown in Figures 2(d) and 2(e); by comparing the two figures, no differences can be visually perceived, which means the on-TFE AoD indeed can well secure display's optical performance.

3.2 *Dual-band Millimeter-wave AoD*

As Figure 3(a) shows, an on-TFE dual-band millimeter-wave AoD was presented [8]. For the AoD radiator, similarly, it is developed in as a rectangle; however, for the reference ground of the 50-Ω feed line, its top (i.e., the part close to the metal mesh) now is designed in a semicircular shape to enable new coverage in the high band. The main performance of the proposed on-TFE dual-band millimeter-wave AoD is shown in Figure 3(b); the qualified bandwidth of –10-dB reflection coefficient can cover 27.31–28.46 GHz and 36.52–40.30 GHz so that in addition to the 3GPP band n261 another popular 3GPP 5G millimeter-wave band n260 (37.0–

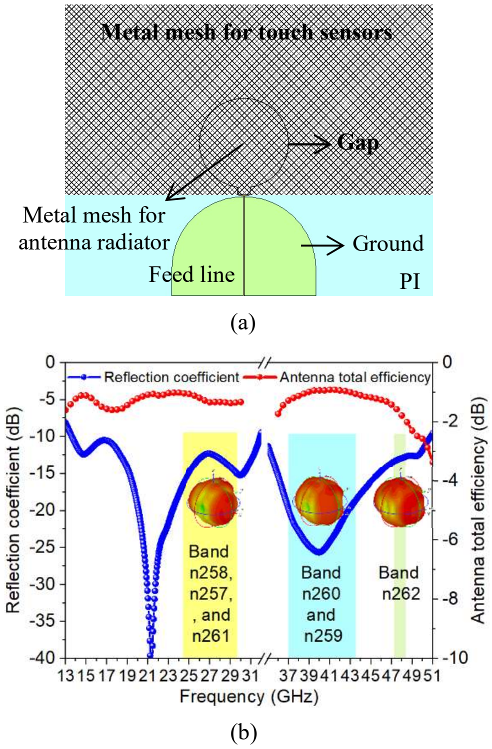

Figure 4. On-TFE wideband millimeter-wave AoD [9]: (a) design; (b) reflection coefficient, antenna total efficiency, and 3-D realized gain patterns at 28.0 GHz, 39.0 GHz, and 47.5 GHz.

40.0 GHz) can be also supported. Besides, the antenna total efficiencies (with the feed-line loss included) in the covered bands n261 and n260 are higher than –2.52 dB and –1.80 dB, respectively; the corresponding peak realized gains at 28.0 GHz and 38.5 GHz (i.e., the center freqyuecy of the band n260) are 1.47 dBi and 2.78 dBi.

3.3 *Wideband Millimeter-wave AoD*

Figure 4(a) shows an on-TFE wideband millimeter-wave AoD [9]; as clearly shown, in addition to the semicircular reference ground of the 50-Ω feed line, the AoD radiator is designed in a circular shape as well to further embrace more bands. What's more, the main performance of the develpoed on-TFE widenband millimeter-wave AoD is shown in Figure 4(b); the –10-dB bandwidths range from 13.63 GHz to 31.85 GHz and from 34.70 GHz to 50.81 GHz so that all 3GPP's licensed 5G millimeter-wave bands n258 (24.25–27.50 GHz), n257 (26.50–29.50 GHz), n261 n260, n259 (39.5–43.5 GHz), and n262 (47.2–48.20 GHz) can be accommodated. In these covered bands, the antenna total efficiency (with the feed-line loss included) of the on-TFE wideband millimeter-wave AoD is higher than –1.88 dB; the peak realized gains at 28.0 GHz, 38.5 GHz, and 47.5 GHz (i.e., around the center freqyuecy of the band n262) are 2.50 dBi, 3.17 dBi, and 1.94 dBi, respectively.

4. Design Evolution

Based on the above, the on-TFE millimeter-wave AoD designs for 5G and 6G single-band, dual-band, and wideband coverage are analyzed; the design evolution with the band(s) supported and the

Table 1. Design Evolution of on-TFE Millimeter-wave AoD.

On-TFE millimeter-wave AoD	**single-band [7]**	**dual-band [8]**	**wideband [9]**
3GPP 5G band(s) supported	n261	n261, n260	n258, n257, n261, n260, n259, n262
Shape of radiator	rectangle	rectangle	circle
Shape of reference ground top	rectangle	semicircle	semicircle

corresponding technique(s) is compared in Table 1 for clear understanding. From the design evolution, it unveils that smooth shapes (such as circular or semicircular ones) for AoD radiators or reference grounds of feed lines can effectively contribute to the broader band coverage (due to wideband impedance matching), so users' experience in wireless communications can be greatly upgraded. Furthermore, the smooth-shaped designs are quite easy to be attained and thus are pretty practical because no complex processes or high costs are needed; therefore, the design techniques can be quickly and widely applied. Over and above wireless communications, on-TFE AoD is able to function as Radars as well for wireless sensing to enrich human-device wirless interactions for more powerful artificial intelligent (AI) devices. Also, with broader band coverage, AoD is more promising for integrated sensing and communications (ISAC) [13], [14], a hot and key technology in 6G.

5. Conclusion

This paper fully discusses the advatanges of on-TFE AoD and systematically reviews the design evolution of three leading on-TFE millimeter-wave AoD developed by us. Moreover, the key design technique for on-TFE millimeter-wave AoD to achieve broader band coverage is pointed out as well for facilitating wide application and inspiring future advances. Further designs maily include wideband dual-polarized on-TFE millimeter-wave AoD, multiband on-TFE microwave AoD, and integration of on-TFE millimeter-wave AoD and on-TFE microwave AoD [15] for even powerful wireless comminunication capabilities in 5G and 6G eras.

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