Preview

# Inkjet-printed invisible antenna facilitates next-generation wireless communication

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**Invisible (optically transparent) antennas are promising technologies due to their widespread applications, ranging from 5G/6G communications using synthetic glass antennas to vehicular communications to cube satellites that can integrate transparent antennas with photovoltaic panels. In a recent issue of *Cell Reports Physical Science*, Glinsek and co-workers showcased the use of digital inkjet printing for fabricating conductive ITO as cost-effective transparent antennas with improved radiation efficiency.**

The fifth-generation (5G) and beyond-fifth-generation (B5G) wireless communication networks are envisioned to provide ubiquitous connectivity, enhanced coverage, ultra-reliable low latency, and high data rates to meet societal and industrial needs.[1–4] Furthermore, 5G and B5G technologies unleash the potential of machine-to-machine communication and the Internet of Things (IoT) to build an ecosystem where networks can provide instantaneous connectivity for billions of connected devices. However, one challenge to the wide deployment of such a level of connectivity is that traditional antennas used in the current communication systems are often large and intrusive. The exponential growth in demand for IoT devices, gateways, and other wireless modules, alongside aesthetics requirements and cost considerations, has driven engineers to research invisible or less visually intrusive antenna systems that can be used in access points and signal repeaters embedded into existing urban infrastructure without spoiling the aesthetic appearance of the environment and architectures. Particularly, "optically transparent" antennas, which can be seamlessly integrated with windows, windshields, solar cells, and display panels (e.g., antenna-on-display technology[3]), are foreseen to maximize the usage of such surface area and, therefore, facilitate the 5G and B5G vision and promise of connecting virtually everything.

Historically, the transparent antenna was first deployed on solar panels of small satellites with limited surface area, such as CubeSats. Since then, a variety of transparent or semi-transparent antennas based on different materials, such as metal meshes, metal nanowire networks, transparent conductive oxides (TCOs), and doped thin metal films,[1–4] have been actively studied. Transparent radio-frequency (RF) and microwave antennas based on wide-band-gap conductive oxides doped with indium are extensively exploited; among them, indium tin oxide (ITO) is the most widely used TCO material, which has been reported to have high optical transmittance (an average transmittance of 85% in the visible spectrum), low resistivity (on the order of $10^{-4}$ $\Omega \cdot$ cm), and good environmental stability.[5] These desirable properties render ITO a promising material platform for transparent electrodes and interconnects in invisible electronic devices. It should be pointed out that ITO films, particularly those fabricated by sputtering or spin-coating techniques, also have several inherent drawbacks, such as brittleness, scarcity of indium, and uniformity over a large area.

Recently, in *Cell Reports Physical Science*, Sebastjan Glinsek and co-workers have demonstrated a digital inkjet printing technology for the low-cost fabrication of ITO-based transparent antennas on a fused silica substrate.[6] Programmable inkjet printing (Figure 1A) allows for direct patterning and low-waste deposition of materials, resulting in significant manufacturing cost savings. This material-efficient manufacturing process consumes six times less material than subtractive processes, such as the photolithographic patterning and etching technique. Moreover, this work exploits a combustion-based synthesis method for the preparation of ITO with increased conductivity. This method can effectively decrease the required annealing temperature to 400°C (compatible with majority commercial glasses) by taking advantage of the highly exothermic reaction between the fuel (acetylacetone) and the oxidizer (indium nitrate). The inkjet-printable inks consist of ethylene glycol added to 2-methoxyethanol-based solutions. To achieve the required conductance for the antenna structures, up to 30 layers were printed, with a total thickness of 120 nm. This inkjet-printed ITO exhibits a high visible light transmittance of 87%, an electrical conductivity of 1,280 ± 90 S $cm^{-1}$ (or sheet resistance of 65 ± 5 Ω/□), and a Haake's figure of merit (FOM) of $4.9 \times 10^{-3}$ $\Omega^{-1}$. The FOM is comparable to the state of the art and approximately half the value reported for a high-quality spin-coated ITO.[7] Such results may be attributed to the combination of fuel- and oxidant-assisted strong exothermic reactions in the combustion synthesis and the multilayer annealing process, which lead to improved crystallinity, enhanced removal of organic residues, and increased crystallite size.

The researchers exploited the drop-on-demand inkjet printing technique to manufacture a meander line-shaped patch antenna based on ITO (Figure 1A). This microstrip antenna with a size of

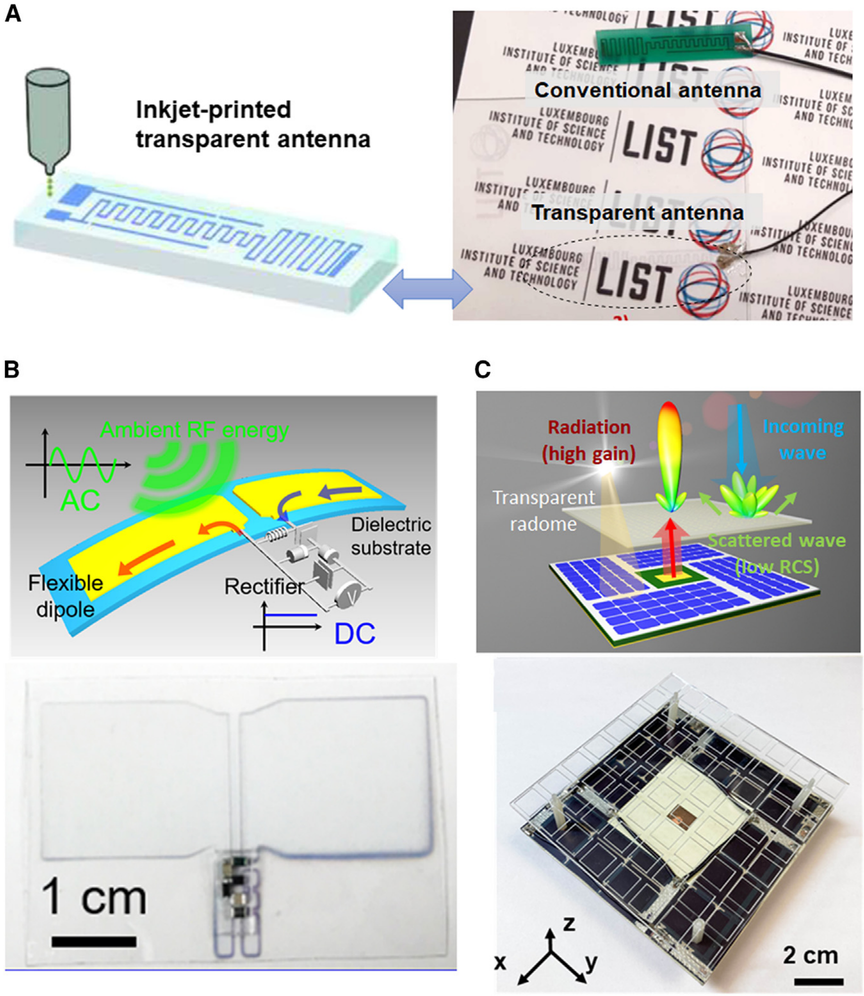


**Figure 1. Optically transparent antennas for the next-generation communication systems**
(A) Schematic of digital inkjet printing for simultaneous deposition and direct writing of ITO-based transparent antenna patterns with minimal material waste.
(B) Transparent antenna integrated with a rectifier for RF energy harvesting, IoT, and passive wake-up radio applications.
(C) Autonomous self-powered transmitter/receiver consisting of a transparent radome that provides beamshaping and protection functions (top), a microstrip patch antenna (middle), and a photovoltaic panel (bottom).
Reproduced from Ha et al.[4]

41.5 × 5.4 $mm^2$ can resonate at 2.4 GHz and provide Bluetooth transmission/reception connectivity at a distance of up to 10 m, with a received signal strength indicator above −80 dBm. Although this is still lower than that obtained using an opaque copper antenna on the flame-retardant (FR), woven glass-fabric reinforced epoxy composite (FR-4) substrate (−71 dBm), it is an encouraging result hinting at conceivable technology for applications in short-range IoT communications. This research also demonstrated an autonomous self-powered communication system powered by a solar panel placed beneath the inkjet-printed transparent antenna. With a proper power management system, the harvested solar energy was used to switch on the sensors, the microcontroller, and the communication module, as well as wirelessly transmit the data to a portable reader such as a smartphone.

The wireless sensor system developed by Glinsek and co-workers is applicable in various real-world wireless communications and sensing systems that require massive deployment of unobtrusive antennas (Figures 1B and 1C). There are plenty of opportunities for continued research in this area. Realization of the holistic sixth-generation (6G) vision, including significantly improved coverage and ultra-low latency, is enabled by massive multiple-input multiple-output (mMIMO) with a large-scale antenna array at the base station and intelligent reflective surfaces (IRSs) formed by arrays of reconfigurable radiating elements.[8] In this regard, transparent and even autonomous self-powered IRSs and mMIMO, which can be invisibly integrated into urban infrastructures, may offer a promising pathway for future 6G communication. Scalable, adaptive manufacturing of large-area transparent antennas and arrays would pose both new challenges and opportunities. Rapid, low-cost roll-to-roll manufacturing or arrayed printing may be viable solutions. Another important open challenge is to simultaneously engineer the optical transparency and electrical conductivity that influences the antenna's radiation efficiency. There is always a paradox or trade-off between TCOs' optical and electrical properties, as increasing the film thickness increases their electrical conductance (which is desirable) but simultaneously reduces the optical transparency (which is undesirable) due to the increased optical path length and, hence, light absorption. In addition, several factors, including scalability, cost, and residual stress (e.g., thermal, interfacial, and growth stresses), in films fundamentally limit the thickness, uniformity, and performance of TCO films. So far, TCOs fabricated by inkjet-printing, sputtering, and chemical deposition methods generally have a submicron thickness, well below the material's skin depth, yielding a relatively large sheet resistance and, therefore, lower radiation efficiency and gain compared to a traditional opaque antenna made primarily of copper. Recently developed multi-layered film structures (e.g., dielectric-metal-dielectric nanocomposites[9,10]) capable of achieving broadband resonant transmission and optical index/impedance matching are another promising route to boost the optical transparency without sacrificing the electrical conductance of the metal film protected by the dielectric coatings. In this aspect, interdisciplinary research involving optical, electrical, and material engineering, as well as innovative antenna design, is essential for improving Haake's FOM, antenna gain, cost, and reliability.

## DECLARATION OF INTERESTS

P.-Y.C. declares interest in transparent antenna technology. L.J.G. declares financial interest in thin-metal-film-based transparent conductor technology.

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