Transparent Antennas: Out of Sight, Out of Mind

How a new transparent antenna material delivers peace of mind solving wireless design challenges of 5G, IoT and automotive safety systems

“THE DEVELOPMENT OF NEWER IOT, 5G, AND AUTOMOTIVE RADAR DEVICES WITH UNIQUE ENCLOSURES MOTIVATES THE NEED FOR ADVANCED ANTENNA MATERIALS THAT CAN MEET STRICT FORM FACTOR REQUIREMENTS. ”

INTRODUCTION

With origins reaching back to ALOHAnet in 1971, a confluence of protocol advancements and mass adoption of devices such as smartphones have cemented "cutting the cord" using RF signals as the preferred method of connectivity for an ever-growing array of data consuming devices. Despite the rapid escalation in wireless speed and the explosion in connected devices, the technology enabling all this connectivity – the antenna – has failed to keep pace with these technological advancements.

With the rollout of 5G necessitating more antennas closer to the point of use to achieve high-bandwidth line of sight connections and manufacturers seeking to retrofit IoT connectivity in a broad range of devices, have performance and design requirements finally exceeded the capabilities provided by existing antenna materials? If antennas could be made transparent, escaping the bounds of an enclosure, could they "hide in plain sight" or be adhered to the outside of existing devices to overcome the challenges of new applications? Better yet, could this new material deliver equal or better performance to traditional materials so not requiring the rationalization of design tradeoffs typically found with new materials?

A new class of transparent conductive material – CNT hybrids – delivers the conductivity required for high performance antenna applications while achieving near transparency to effectively make antennas disappear. Currently being used to revolutionize IoT products, 5G antenna arrays, and automotive sensors, this white paper presents a range of commercially available alternative materials and how the CNT hybrid empowers designers with new options for innovation.

NEXT-GEN MATERIALS BRING NEXT-GEN ANTENNAS

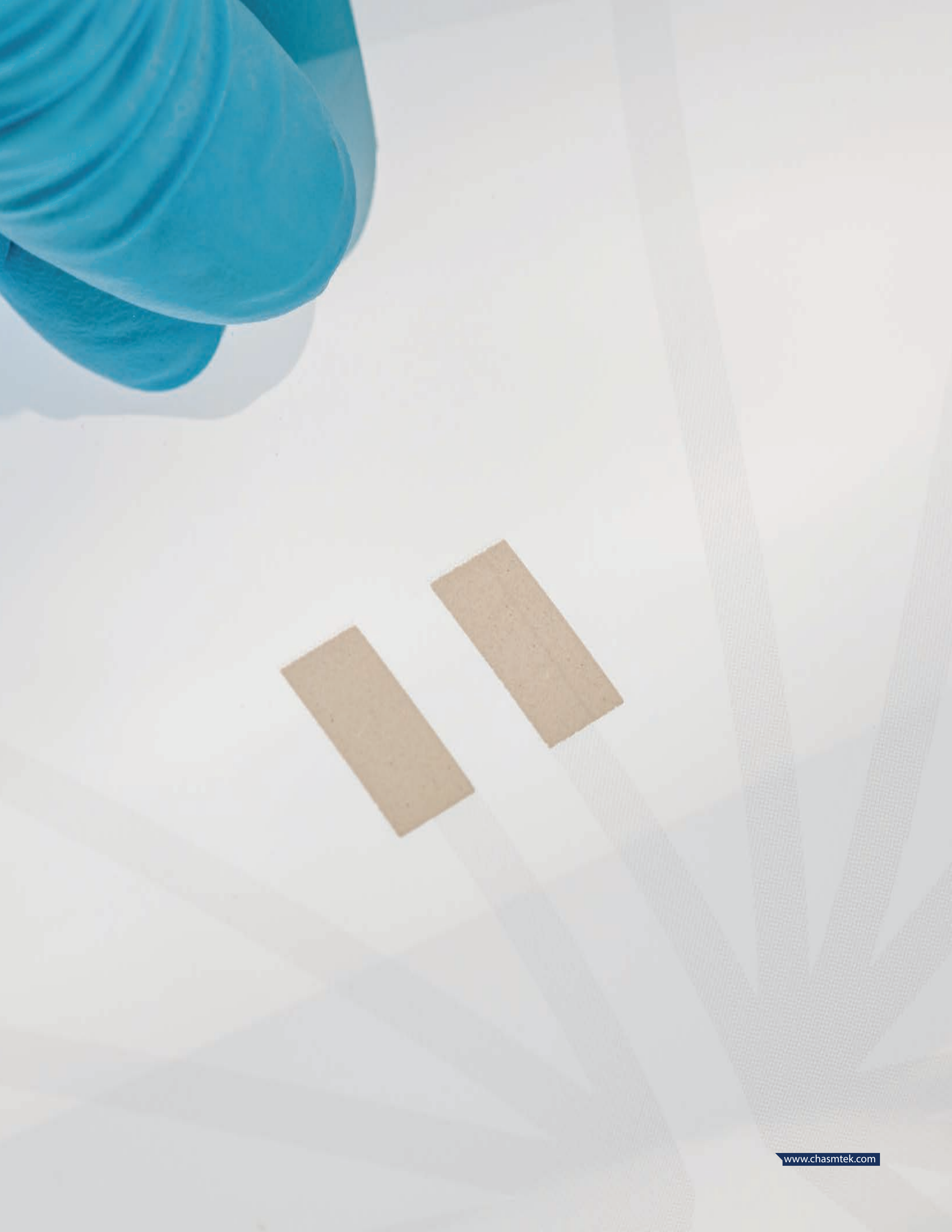
It is often said that necessity is the mother of invention, but the history of science and technology has shown that the reverse is often true. As the telecom industry has grown and matured, and as higher over-the-air data rates have become available, computing workloads can be moved from the cloud to the edge, which opens up applications that were formerly the stuff of science fiction. Future IoT devices and 5G products will be processing more data at the edge than ever before, and all while communicating with each other and the cloud. Newer automobiles will also need to communicate with each other and smart greater use of short and long-range radar for ADAS systems, all operating at high GHz frequencies.

The key factor enabling these systems and applications is highly efficient antennas with small form factors and low loss tangent at 10-100 GHz frequencies. When we look at desired form factors for 5G, IoT, and automotive systems, a flexible, transparent antenna material enables new applications that are difficult or impossible with current materials. experience.

The current antenna solution for these products is copper phased array antennas, which must be etched onto a PCB laminate with low loss tangent at such high frequencies. Other small form factor solutions on the market include chip antennas, a variety of SoCs, and transceiver modules with integrated antennas operating in WiFi, Bluetooth, cellular, and K or W radar bands. These solutions respectively provide antennas with very low sheet resistance or high efficiency in specific RF bands. However, the specialized PCB laminates required to support these solutions carry high costs and restrict designers to planar antennas behind an enclosure. As a result, the enclosure can still interfere with antenna transmission/reception.

TCFs are one class of materials that provide a solution to these design challenges in the above areas. Any TCF must provide high efficiency, high gain, low cost, and low profile, as well as being easily fabricated with unique geometry. A flexible TCF with low sheet resistance can be easily molded to a device enclosure and function as a highly efficient transparent antenna. By engineering the supporting substrate, it becomes possible to tune absorption to the desired RF band without sacrificing transparency at visible wavelengths. Using a transparent frequency-selective surface (FSS) material as a ground plane also allows the directionality of the antenna in various frequency bands to be tuned. This ability to adapt the material to unique enclosures, tune the absorption band, and tune the radiation pattern with an FSS helps designers maximize signal strength and provide desired directionality. Cost is also a critical factor to ensure scalability and to satisfy upcoming market demand for TCFs, which is expected to exceed $5 billion by 2022.

Image: Courtesy CHASM - TCF Antenna AgeNT-1



THE CURRENT STATE OF TCFS AS POSSIBLE ANTENNA MATERIALS

Although not particularly new, the variety of flexible TCFs reported in the literature and on the market is extensive, and many materials have been specialized for different products. The current range of flexible TCFs includes metal oxides, conductive polymers, metal nanostructures, and MMs.

While these materials can be fabricated on a flexible substrate like PET, they all carry some common disadvantages that inhibit scalable manufacturing or their use as high efficiency antenna materials in high-GHz RF products. The primary design requirements for commercializable flexible TCFs as antenna materials are:

- Low sheet resistance: Designers that want flexible TCFs for antennas need a material with sheet resistance not greater than 1 OPS.
- High VLT and low haze: Transparent conductors should be nearly invisible (at least 90% VLT) and have less than 5% haze.
- Simple manufacturing process: The fabrication process for an ideal flexible TCF should be easy to scale and carry low costs. The number of deposition, curing, etching, and cleaning steps should be minimized.
- Patterning over a large area: A larger has a larger absorption cross section for detecting low-level signals. A flexible TCF antenna should be scalable up to any desired size with patterned geometry.

Metal nanostructures

Metal nanostructures satisfy the first design requirement listed above, but they have significant haze and are translucent with low VLT in the visible range. They are also costly to manufacture on transparent flexible substrates at the scale needed for their envisioned applications, requiring processes like photolithography for substrate patterning, followed by sputtering, solution growth, or vapor deposition.

> **"ANY TCF MUST PROVIDE HIGH EFFICIENCY, HIGH GAIN, LOW COST, AND LOW PROFILE, AS WELL AS BEING EASILY FABRICATED WITH UNIQUE GEOMETRY. "**

MM Films

MMs are similarly un-promising as GHz antenna materials thanks to their sheet resistance of at least ~3 OPS. These materials can be nearly invisible as long as the mesh size is less than ~6 microns, but fabricating this pattern requires an electroless copper process or photolithography process, both of which are followed by etching.

Patterned Transparent Metal Oxide Films

Other materials, such as metal oxide TCFs, only satisfy the fourth design requirement. Getting sheet resistance below 2.5 OPS is a major challenge, making these materials unsuitable for use as high-efficiency antennas. The morphology of these materials makes them hazy with insufficient VLT (up to ~80%) for antenna applications. The patterning process for metal oxide TCFs is inefficient in that it requires a subtractive process, or it requires direct pattern deposition with a photolithographic process. Using photolithography allows the desired conductor pattern to be deposited directly on the substrate, but it requires multiple develop, etch, strip, and cleaning steps, just as is the case with MMs. Laser ablation is also useful for patterning on glass, but it can damage a flexible plastic or polymer substrate. This process also requires significant laser time, which increases overall patterning costs.

Conductive Polymers

Conductive polymers run the gamut on satisfying these requirements. Ag nanowires mixed with PEDOT:PSS (a popular TCF) provides very high transparency, but its sheet resistance is much too large for use as an antenna. It remains to be seen whether a conductive polymer TCF material with high VLT can be found and produced at scale.

COMPARING CURRENT OPTIONS

Material	Sheet resistance (OPS)	VLT
Metal nanostructures	0.3 to 8	50% to 90%
MM films	2.5 to 10	Up to 90%
Metal oxide films	2.5 to 25	Up to 80%
Conductive polymers	~10 to ~100	Up to 90%

FINDING ALTERNATIVE MATERIALS

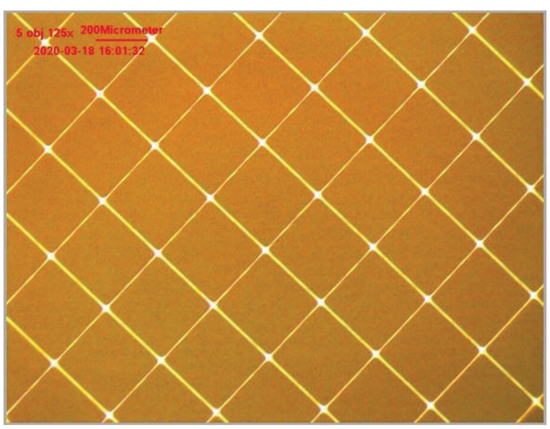
Obviously, it has been difficult to find materials that can satisfy all the above requirements. A clear alternative is a hybrid material that provides the high transparency of an open MM with low sheet resistance and fewer manufacturing steps. A new class of printable carbon nanotube hybrid materials offers a solution to this unique set of problems and will enable a new class of IoT, 5G, and automotive radar devices with flexible transparent printed antennas.

Hybrid Metal Mesh and Carbon Nanotube TCFs

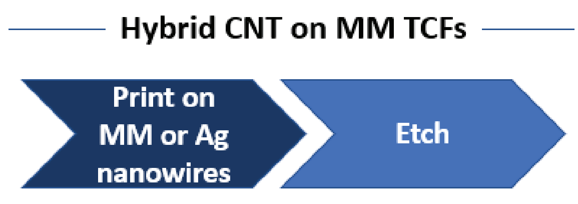
Any flexible transparent antenna material needs to have less than 1 OPS sheet resistance in order to provide efficiency and gain that are comparable to patch or microstrip antennas on PCBs. The newest class of materials also needs to be printable, flexible, and highly transparent at visible wavelengths. Once paired with a transparent flexible FSS material on the back side of the antenna, designers now have another lever to control directionality in specific frequency bands.

The newest class of hybrid TCF materials can be formed by depositing or printing a CNT ink deposited on a Cu MM substrate, where the MM is available on a flexible transparent material such as PET. This type of TCF can be manufactured with fewer steps and competitive costs compared to printed metal oxide TCFs. Designers then have freedom to place a conformal antenna anywhere on the device enclosure, including on optical elements. This also leaves additional space on a PCB that would have been dedicated to a specialty SoC, wireless module, or printed Cu antenna (e.g., microstrip antenna or patch antenna array).

The SEM image below shows an example of such a hybrid material with single-walled CNTs printed on a Cu MM. The stack of PET, MM, and CNTs forms a unique flexible TCF with lower sheet resistance and higher VLT (> 95%) than metal oxide TCFs, bare metal nanostructures, MMs, and conductive polymer TCFs. The hybrid CNT film also encapsulates the conductive substrate, which provides additional environmental stability and ensures the entire film remains conductive if micro-fractures form during bending.

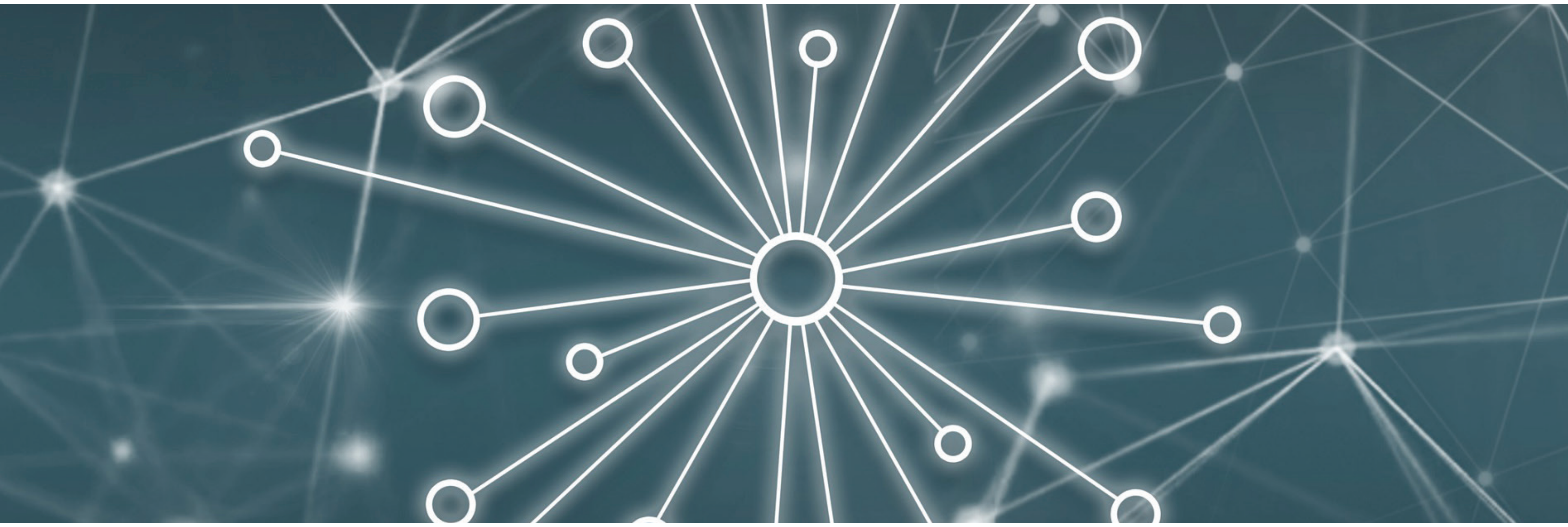


This type of film has a very simple fabrication process compared to patterned TCFs made from metal oxides, nanostructures, or meshes. CNTs can be placed in an ink suspension, which can then be printed on MM/PET substrates. When coated on the substrate, the CNTs and metal form a flexible TCF with <1 OPS sheet resistance. Rather than using sputtering and ablation processes for patterning, the CNT ink can be printed in the desired pattern, and the uncoated MM substrate layer can be removed from PET with an etchant.



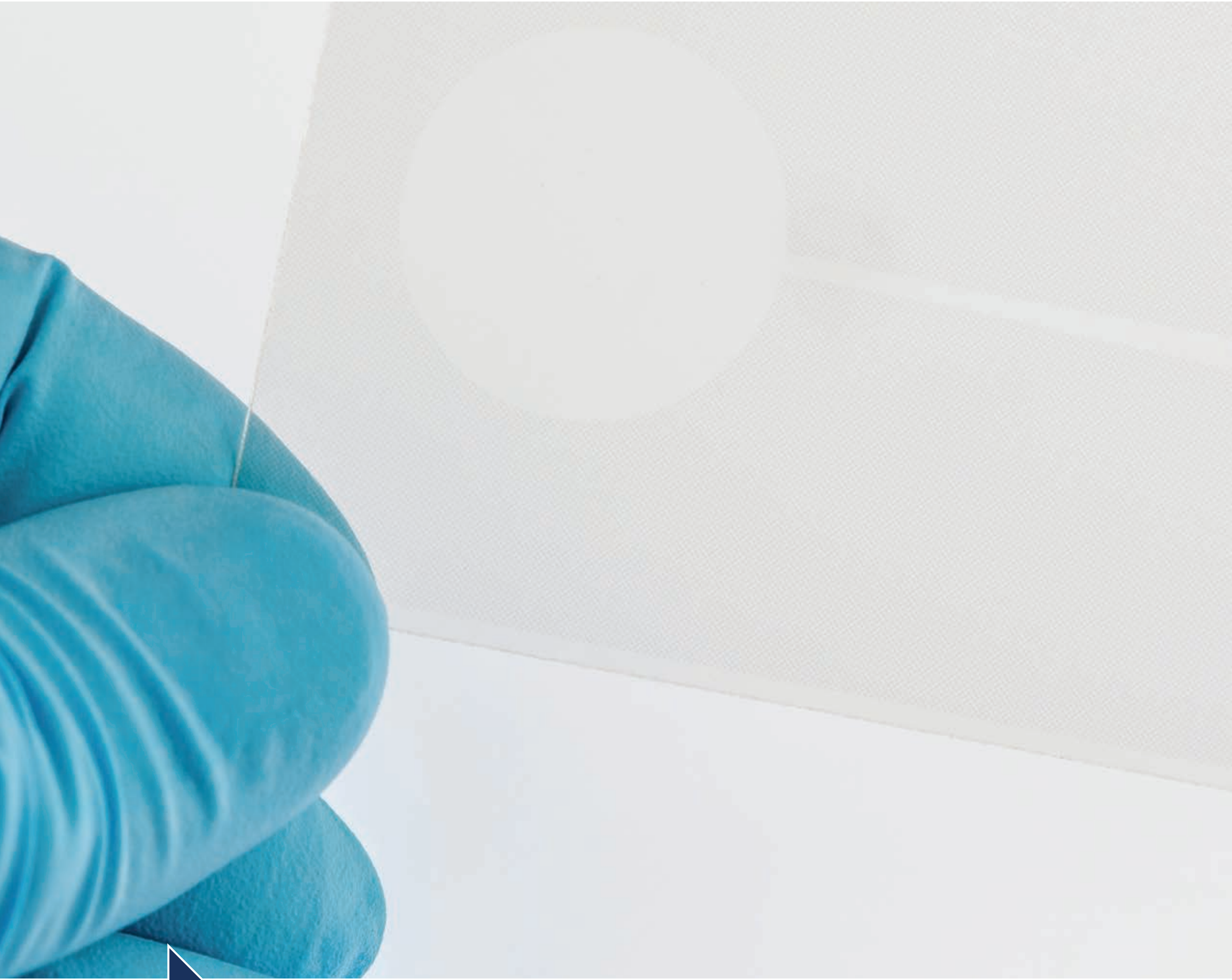
Manufacturing Process for CNT Hybrids

COMPARING CURRENT OPTIONS & CNT HYBRIDS



Material	Sheet resistance (OPS)	VLT
CNT Hybrid	~1	94%
Metal nanostructures	0.3 to 8	50% to 90%
MM films	2.5 to 10	Up to 90%
Metal oxide films	2.5 to 25	Up to 80%
Conductive polymers	~10 to ~100	Up to 90%

The structure of this type of hybrid CNT film is ideal for printing a patterned antenna structure, where the underlying conductive substrate determines the opacity of the hybrid TCF. When working with an MM substrate, VLT can be kept far above 90% and haze can be kept low as long as ~90% of the MM is left open for CNT deposition. When working at higher RF frequencies, the required gap region in the MM film is smaller (i.e., one-half the carrier wavelength). This gives a designer a simple way to control absorption transmitting/receiving frequency of a TCF antenna.



“ WITH UNIQUE HYBRID CNT FILMS ON FLEXIBLE TRANSPARENT SUBSTRATES, IOT, 5G, AND AUTOMOTIVE RADAR DESIGNERS CAN MOLD A TRANSPARENT ANTENNA TO AN ENCLOSURE, OPTICAL ELEMENT, OR FOLDABLE ELEMENT IN THEIR DESIGN. “

BRINGING IT TOGETHER

With unique hybrid CNT films on flexible transparent substrates, IoT, 5G, and automotive radar designers can mold a transparent antenna to an enclosure, optical element, or foldable element in their design. For IoT and 5G applications, designers can tailor the emission pattern and directionality through the use of a flexible TCF and transparent FSS as a flexible substrate. For radar, designers can create integrated optical/RF sensors as these transparent antenna materials could be molded onto optical devices, such as cameras and lidar systems.

This hybrid CNT solution gives designers a flexible transparent antenna that can be mounted anywhere on the device, including directly on a PCB. It also gives antenna designers the ability to tailor the bandwidth, resonance structure, directionality, and other antenna characteristics while preserving high VLT with low sheet resistance. Next-generation 5G-capable IoT and automotive products need advanced antenna designs that can only be provided by hybrid CNT TCFs.

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