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Nathan D. Orloff,[1] Rick Ubic,[2] and Michael Lanagan[3,a)]

AFFILIATIONS

[1]National Institute of Standards and Technology, 325 Broadway Boulder, Colorado 80305, USA
[2]Micron School of Materials Science and Engineering, Boise State University, 1910 University Drive, Boise, Idaho 83725, USA
[3]Department of Engineering Science and Mechanics, Penn State University, N329 Millennium Science Complex, University Park, Pennsylvania 16802, USA

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[a)]**Author to whom correspondence should be addressed:** mxl46@psu.edu

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Next generation communications are inspiring entirely new applications in education, healthcare, and transportation. These applications are only possible because of improvements in latency, data rates, and connectivity in the latest generation. Behind these improvements are new materials and devices that operate at much higher frequencies than ever before, a trend that is likely to continue.

Beyond these exciting applications, higher frequency millimeter waves (mmWaves) may also address a growing problem with capacity[1,2] [Fig. 1(a)]. Today, most capacity problems occur when large numbers of wireless connections or applications access the network at the same time at any single location. As wireless internet connections far surpass wired connections and wireless data usage has grown exponentially for more than 10 years,[3] many believe that capacity problems will spread without access to new bandwidth.

Seeing both an opportunity to spur innovation and a chance to tackle a serious problem, regulators around the world auctioned new mmWave bands for the development of domestic cellular telecommunications. In the United States of America, the Federal Communications Commission (FCC) held spectrum auctions,[4] creating licensed bands at 24, 28, 37, 39, and 47 GHz that raised over $10B USD[4] for new research and infrastructure. Likewise, regulators in Europe, Asia, Australia, held similar auctions, also raising billions of dollars to spark innovation, commerce, and industry.

In this editorial, we group these bands collectively as 5G mmWaves [Fig. 1(b)], but mmWaves technically covers the bandwidth from 30 to 300 GHz.

Unlike prior generations, new mmWave communications are a major change to hardware rather than just software. That is because new mmWave hardware must operate at frequencies that are more than ten times higher than conventional 3G and 4G technologies. Changing hardware is no small feat. Industry's push to mmWaves required improvements in the underlying materials, architectures, models, and even measurement science.

For example, materials integration and new transistor structures are currently being explored in new transistor topologies for higher frequency and power.[5–8] Thin film magnetic materials are currently being developed for integrated circulators on wide bandgap semiconductors, allowing for simultaneously transmitting and receiving data.[9]

When designing high-speed interconnects, antennas, and integrated passive devices, several performance factors can be improved with low-loss dielectric materials with tailored permittivity. Low permittivity shortens propagation delay and mitigates signal loss; it also can leverage larger device geometries that decrease sensitivity to fabrication tolerances. Glass and glass ceramics are ideal candidate dielectric materials for low loss substrates because of their low loss and smooth surfaces for metallization, which is important to reduce metal loss in a transmission line structure.[10,11] Higher permittivity ceramics and glass ceramics with low dielectric loss and temperature stability are important for mmWave resonators and filters.[12,13] Dielectric materials must also be integrated with conductors to achieve transmission lines with low attenuation, electromagnetic shields, and antennas with wide operating range.[14–16] Replacing metals with dielectrics has also been proposed to reduce transmission loss and increase antenna performance.[17,18] Accurate electromagnetic property assessment is important for understanding the fundamental polarization contributions to permittivity, permittivity, and loss in the mmWave frequency range.[19,20]

As 5G mmWaves handsets rollout, demand will push technology to high frequencies and more complex device architectures. As frequencies advance into the THz region, the frontier of the

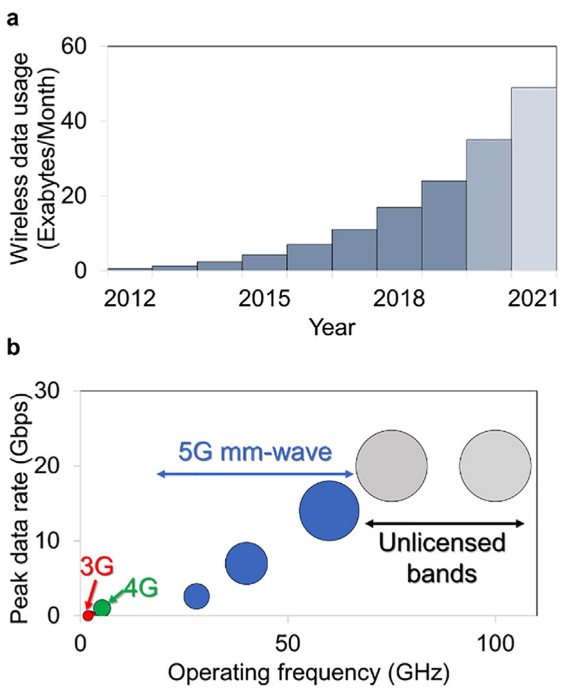

FIG. 1. (a) Wireless data usage grew exponentially over the last decade. Data reproduced with permission from See https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html for "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022 White Paper-Cisco." (b) A plot of the peak data rates vs the operating frequency where the diameter of the circle is the bandwidth.

electromagnetic spectrum will be expanded beyond 5G and new scientific and technological challenges will need to be surmounted. Propagation loss through free space becomes more important with increasing frequency and is a major strain on battery life of mobile telecommunication devices. To make up for propagation loss, phased array antennas, based on tunable materials and devices, will be developed to narrowly focused beams, created through phased array antennas, which will reduce the overall power requirements.[21] Alternative device solutions remove the power source.[22] Arrays and lenses have been proposed to create highly directed mmWave beams.[23] Antenna arrays will require tunable dielectric materials where the permittivity changes with the applied electric field.[24] Ultimately, the benefits of advanced materials and devices must be demonstrated at the system level, where electromagnetic concepts, such as beam forming and doppler, are important for multiple input multiple output (MIMO) and mobile communication platforms.[25]

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DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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