EXECUTIVE SUMMARY

Materials for 5G: Opportunities in mmWave Substrates

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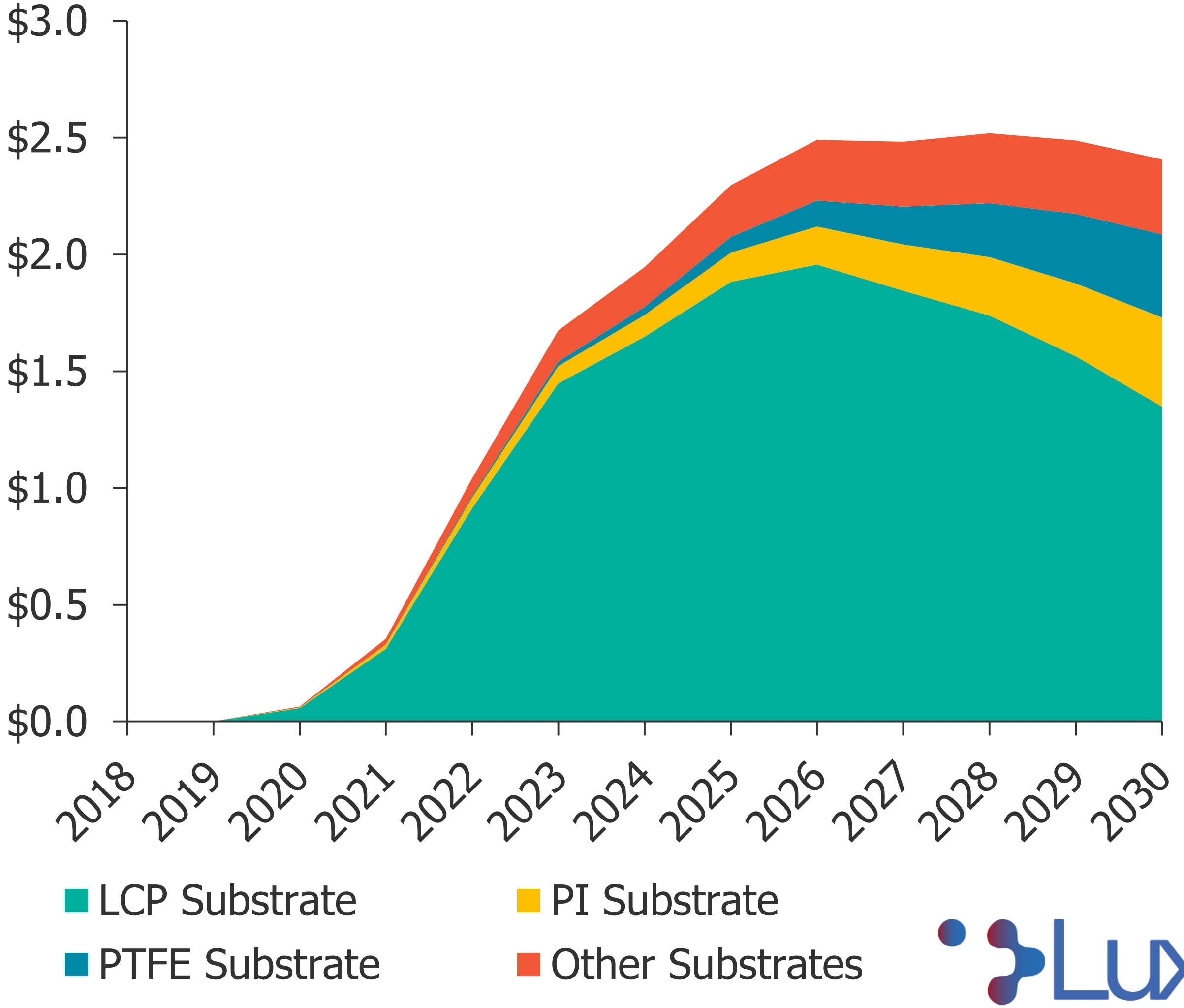
Executive Summary

- As 5G infrastructure rolls out, it will create demand for new materials for antenna substrates that can support high-frequency operation.
- Several materials, including liquid-crystal polymers (LCP), polyimides (PI), and polytetrafluoroethylene (PTFE), will compete with other emerging materials to meet this demand.
- The market size will reach 14,000 MT of material and $2.3 billion in 2030, with uses in mobile phones leading, followed by base stations; 5G infrastructure build-out picks up after 2023.
- LCP will be the leading material choice, but as volumes grow, falling prices for PI and scale for PTFE will lead to growing market share.
- In the longer term, other uses like automotive radar can create even greater demand for high-frequency materials, aided PI and PTFE further.

mmWave Substrate Market

U.S. $ billions

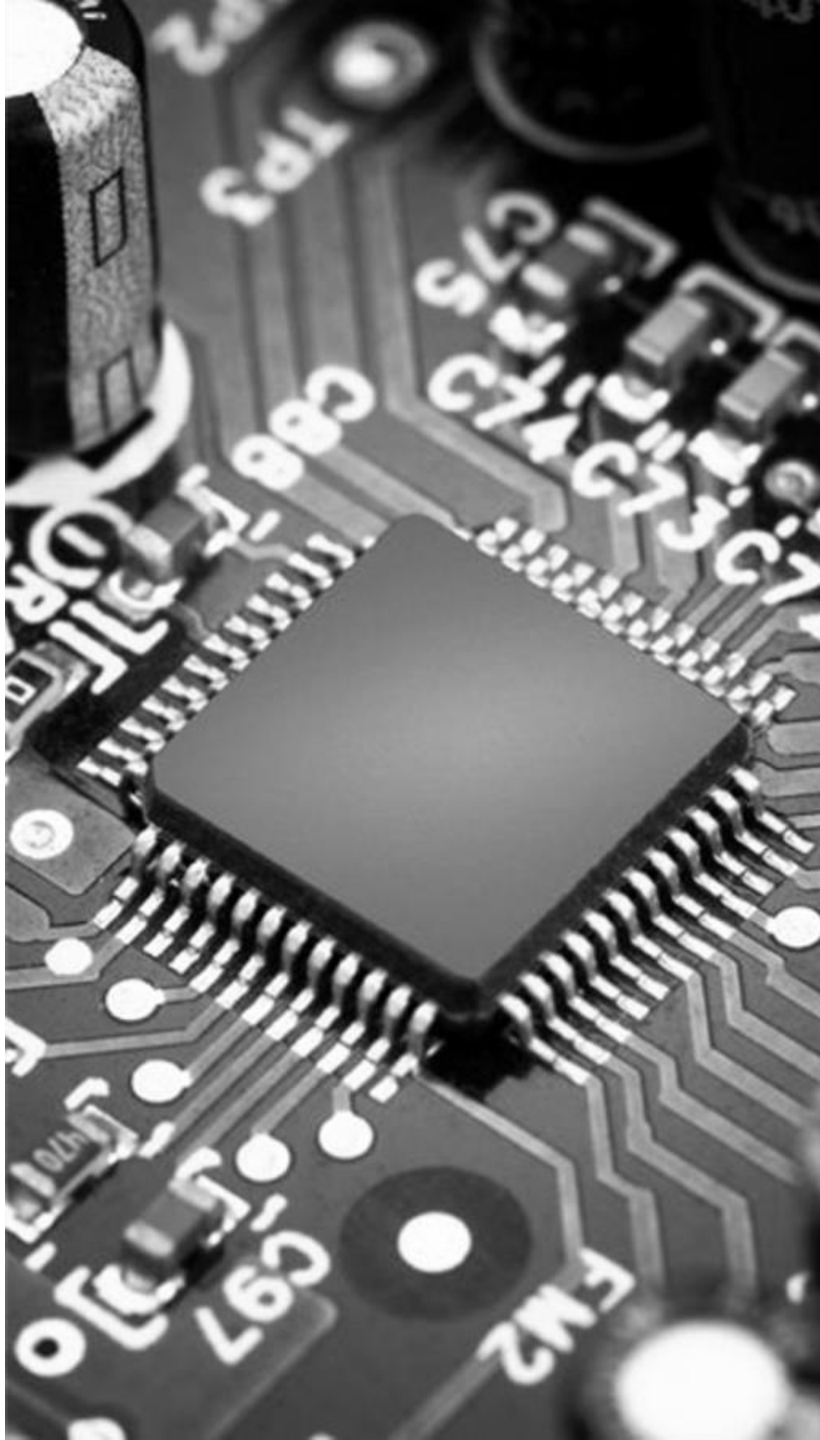


mmWave infrastructure rollout will require new materials

Of the three 5G technologies, **this report focuses on high-band, or mmWave**, because the need for new materials is most urgent at the highest frequency.

The full report:

- Briefly reviews progress on 5G rollout to date
- Identifies the unmet material needs for mmWave technology and reviews the current technology options and emerging alternatives
- Highlights innovative groups that are already beginning to tackle these challenges
- Forecasts the future market demand for these materials and the expected market share for different materials



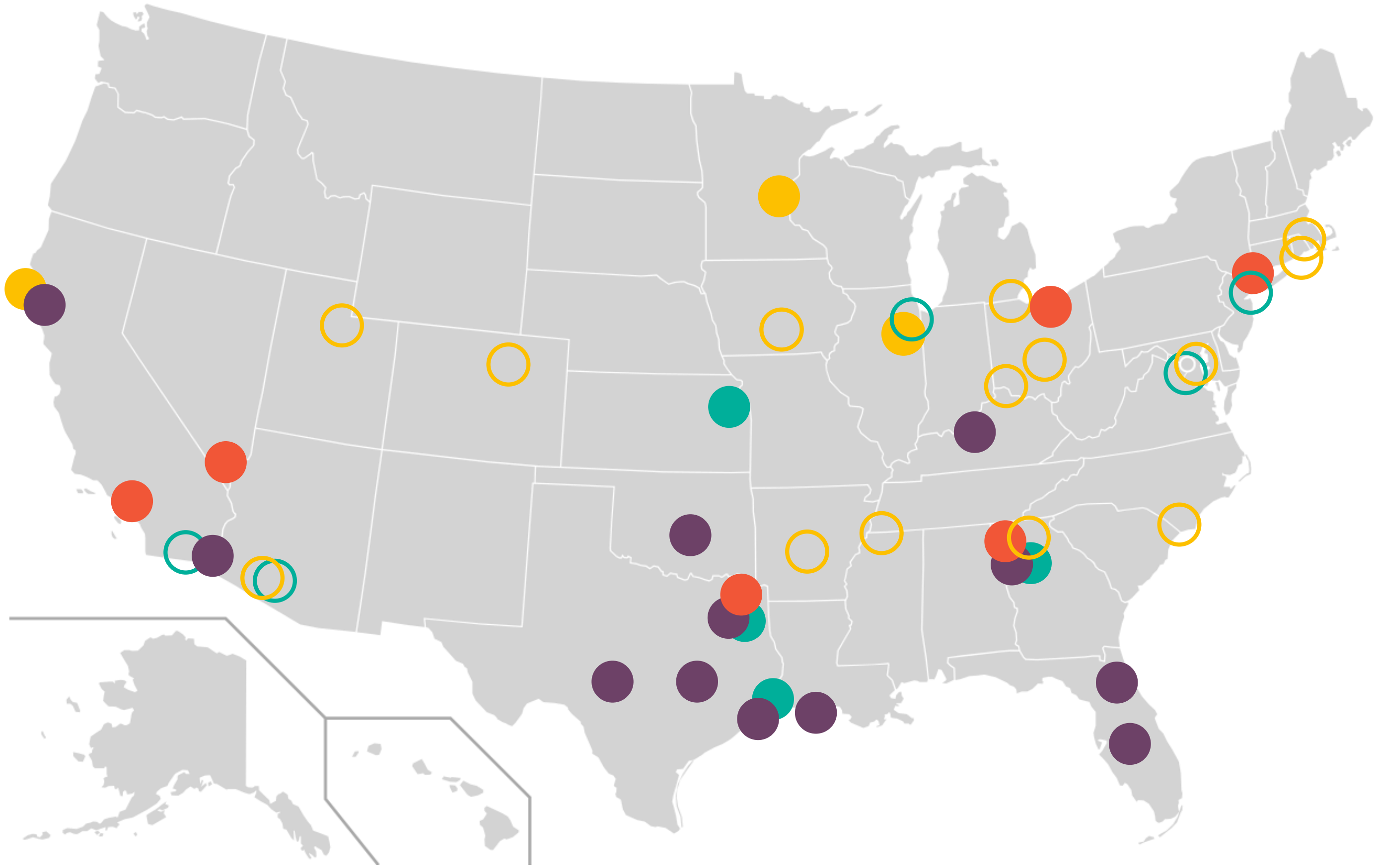
5G rollout: The U.S. has become a 5G battleground

verizon
Technology deployed: **mmWave**

AT&T
Technology deployed: **mmWave**

Sprint
Technology deployed: **Massive MIMO**

T-Mobile
Technology deployed: **mmWave**



● Currently Deployed

○ Projected, End of 2019

Five important metrics for substrate materials will impact materials selection

Dielectric constant: mmWave requires very low dielectric constant (Dk). At high frequencies, the dielectric properties of the material greatly impact the performance of the antenna. In addition, dielectric constant can change with temperature, complicating design.

Dissipation factor: Perhaps even more crucially, mmWave substrates also require low dissipation factor (tanδ, or loss tangent) materials, so less energy from high frequency waves passing through is lost in the substrate material. Circuit designers can work around high dielectric constants, but will find it much more difficult to work with materials that dissipate electromagnetic energy at the high frequencies of mmWave.

Moisture absorption: Small variations in properties have larger impacts at high frequencies, complicating the design process. The ideal substrate would be totally consistent across frequencies, temperatures, and moisture levels. We take low moisture absorption as a metric of stability; water's high dielectric constant may cause major issues at high frequencies if substrates are not water-resistant.

Cost and **manufacturability:** High-performance materials are often expensive and can present challenges in printed circuit board (PCB) production. Common challenges include bonding copper to the substrate, machining features in the substrate, and matching the coefficient of thermal expansion (CTE) between materials – and of course, switching to unfamiliar materials requires time to educate manufacturers. That said, ease of manufacturability can help offset high raw material costs.

The alternative material choices fall into two main groups

The groups are divided by market maturity: One group is the leading contending materials in the market today; the other is a still-emerging set of alternatives. More complete descriptions of each material are provided on the following slides.

Leading materials

- Polyimides (PI)
- Polytetrafluoroethylene (PTFE)
- Liquid crystal polymers (LCP)
- Low-temperature co-fired ceramics (LTCC)

Emerging alternatives

- Modified epoxy
- Phenolic resins
- Polyphenol ether (PPE)
- Polyether ether ketone (PEEK)
- Glass
- Flexible ceramics

Leading materials: PI

Polyimides are a class of high-performance polymers that have been in mass production since 1955, mostly used today for aerospace, automotive, insulation, and flexible PCB applications. They have high heat tolerance, mechanical toughness, and thermal stability, but have poor moisture absorption for 5G applications. Recent modifications aim to decrease their dielectric constant and undesirably high moisture absorption.

Example Metrics	
Dielectric Constant	2.4
Loss Tangent	0.015
Moisture Absorption	0.3%

Key Players:

DAIKIN, JFE, KOLON, DOOSAN, Kaneka, DUPONT, Hitachi Chemical, NIPPON STEEL, TOYOBO, TORAY

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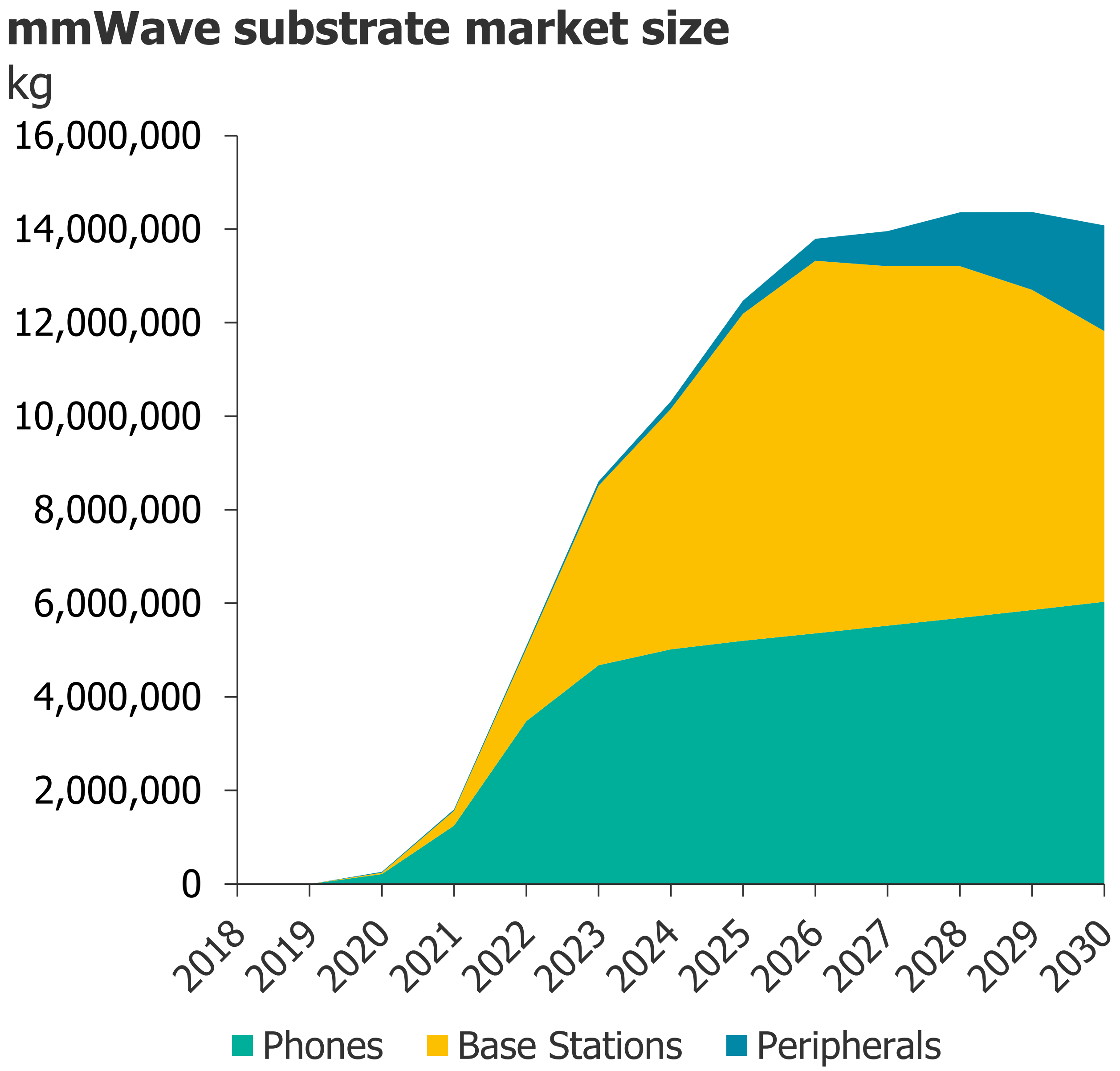
mmWave substrate demand will reach 14 kMT by 2030

Cell phones should initially take the most market share, until about 2023, when it levels off as 5G achieves full penetration. The market for substrate in phones will increase quickly through 2023 to 5 kMT and gradually increase to 6 kMT by 2030.

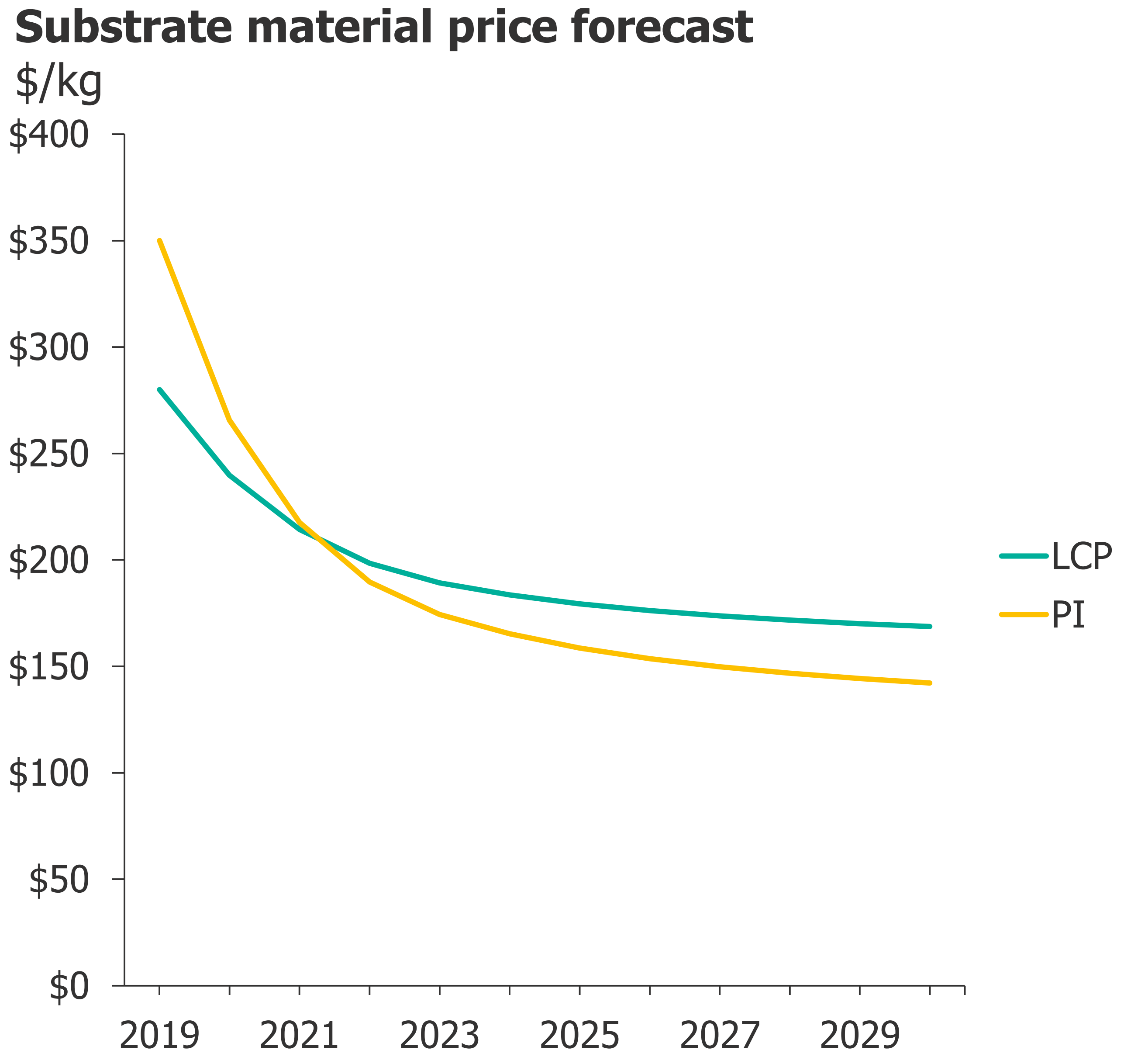
5G-capable base stations begin to be rolled out in earnest in 2023, exploding to take by far the most market share through 2028. The market in base stations will peak at 8 kMT in 2026, dropping off afterward as 5G buildout slows as the demand increasingly comes from replacing base stations – falling to 6 kMT by 2030.

Peripheral substrate demand will grow more steadily after 2025 to reach 2.3 kMT by 2030.



Scale-up will have only moderate impact on prices

Price will be main driver of materials choices once materials meet core performance needs. The market for substrate materials will be competitive, which will keep prices of materials tied to cost of production. The cost of PI and LCP will fall on an experience curve as production scales. Today, PI for substrates is costlier than LCP even though in general PI is cheaper because there is less modified PI on the market. However, PI will decrease in cost at a faster rate after the modified processing for PI scales up. We don't expect substantial changes in PTFE prices, as these materials are already used in substantial volumes for automotive radar applications, and adoption of PTFE in mmWave is likely to be limited in the near term.



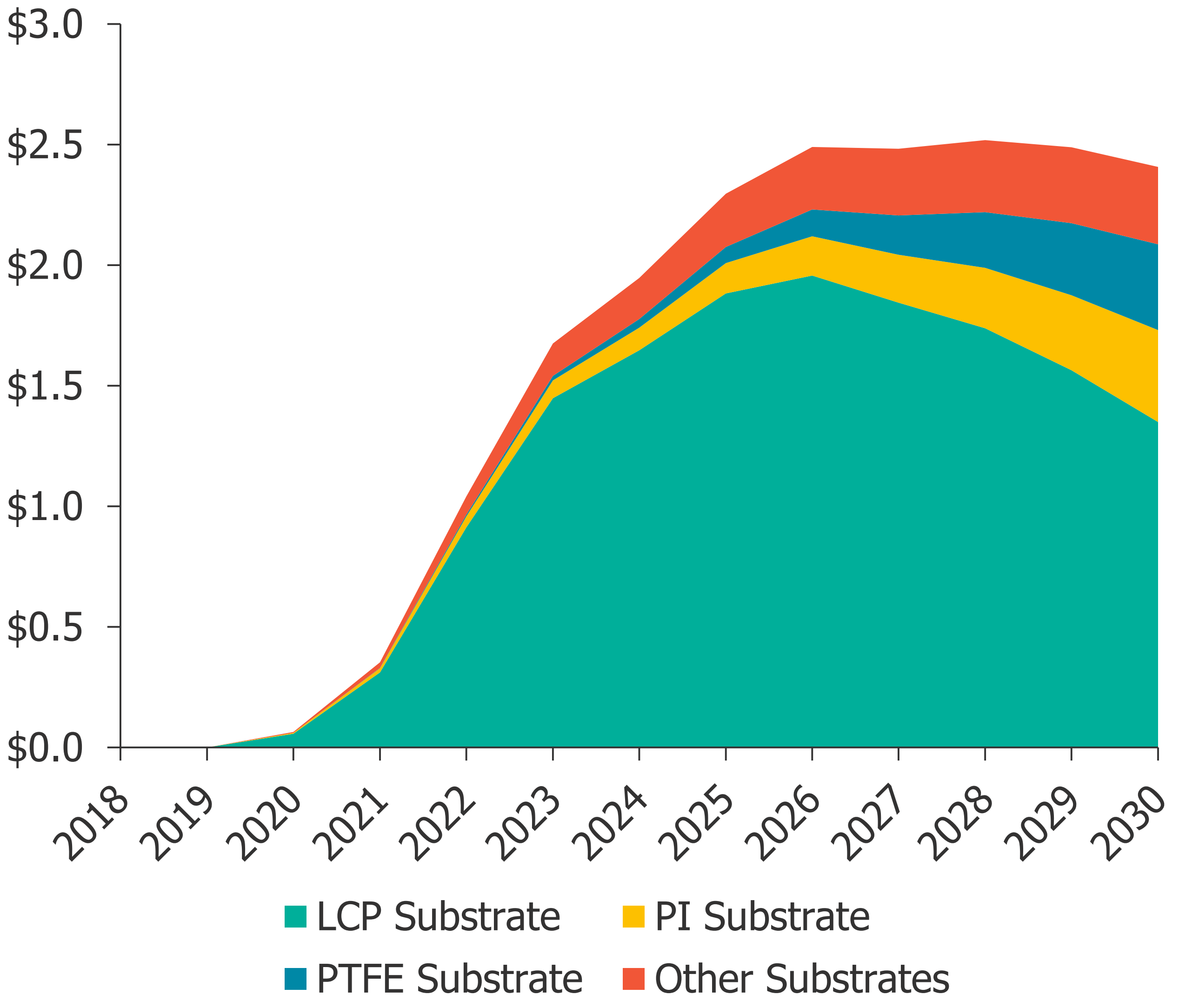
mmWave substrate demand will reach $2.3 billion by 2026

PI will still take a large percentage of the mmWave substrate market by monetary value, though a significantly smaller proportion than by mass, because of its lower costs. Even though mmWave substrates will use a modified and higher-performing PI, we expect processing costs to be closer to those of existing materials once PI reaches market.

The PI substrate market will reach a value of $380 million in 2030. LCP will hit a maximum of nearly $2 billion in 2026 and then drop to $1.35 billion by 2030. PTFE should steadily increase to $350 million by 2030. All other materials will form about $300 million in market value.

mmWave Substrate Market

U.S. $ billions



LCP is likely the near-term winner, but PI and PTFE are better long-term bets

Our forecast has the total mmWave substrate market reaching $2.3 billion, with LCP emerging as the dominant substrate material. **There is little risk of the substrate market being much smaller than this forecast**, as the technical drivers for mmWave and the demand for high data rates necessitate this technology. **However, there is a real chance that the substrate market is much larger than our forecast,** either due to faster-than-expected proliferation of mmWave or due to crossover of materials into other high-frequency applications like radar.

What's more, past 2030, it is nearly inevitable that the high frequency band will become more commonly utilized for everything from industrial devices to consumer electronics to mobility applications. This will result in **higher volume demand for mmWave substrates, thus creating favorable market conditions for PI and PTFE.**

The market will care most about **material properties that are good enough**, without necessarily being the best, **with low cost and widespread availability**. LCP makers will have to try to scale as quickly as possible to reduce costs without overscaling, all while fending off competitive threats from PI and LCP. In addition, players producing any of these materials will have to watch out for a truly disruptive entrant – such as the development of an epoxy grade that's suitable for high-frequency applications. Given that all these technologies will play a role, most materials players should focus on the solution that fits their expertise – but consider taking more of a portfolio approach to hedge bets if resources permit.

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