Exploring advances in microwave and millimeter wave devices

As this report explores up-to-date improvements in RF and microwave power transistors for power amplifiers, it sheds new light on gallium nitride (GaN)-based power transistors. In addition, the report focuses on the latest advances in passive components, and unveils trends in millimeter wave monolithic ICs (MIMICs).

By Ashok Bindra, editorial director and Keith Vick, technical contributing editor

As the demand for higher bandwidth and frequencies in wireless and wirleline applications continues to climb, while cost and size continues to go downward, the need for better performing RF and microwave/millimeter wave ICs, discretes, modules and passive devices is far greater today. Thus, the efforts to improve components from capacitors at one end to millimeter wave monolithic ICs at the other extreme are in full swing. This report looks at some of these developments.

For instance, in the RF and microwave power transistors arena, suppliers continue to tap advances in material science, process techniques, transistor structures, and packaging technologies to drive performance of lateral-diffused metal oxide semiconductor (LDMOS) FETs, gallium arsenide (GaAs) MESFETs, GaAs/InGaP and silicon germanium (SiGe) heterojunction bipolar transistors (HBTs), gallium nitride (GaN) heterostructure FETs (HFETs) and high electron mobility transistors (HEMTs), including silicon carbide (SiC) FETs, to new heights.

While proponents like Agere Systems, Advanced Power Technology RF, Cree Microwave, Freescale Semiconductor (formerly Motorola Semiconductor), Philips Semiconductors, M/A Com, and STMicroelectronics amongst others continue to make significant improvements in RF LDMOS power transistors for wireless infrastructure applications, developers are tapping the benefits of new compound semiconductor material GaN with novel transistor structures to compete against LDMOS devices in the 2 GHz range. Due to their high breakdown field, high electron saturation velocity, high power density, and high operating temperature, AlGaN/GaN HFETs offer attractive alternatives to microwave power amplifier designers. For example, AlGaN/GaN HFET structures can achieve gate-to-drain breakdown voltages of around 100 V/µm and maximum current densities exceeding 1 A/mm, resulting in power densities several times higher than commercially available devices.

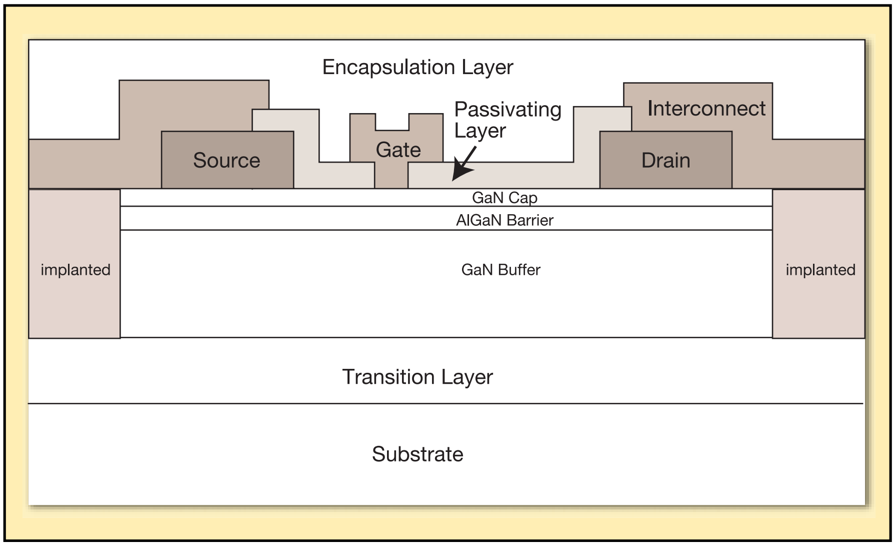

Figure 1. Cross-section of GaN heterostructure FET (HFET).

GaN-on-Silicon

To make it cost competitive with other technologies, work has been undertaken to develop GaN transistors on low-cost silicon substrates. Using its patented Sigantic GaN-on-silicon growth technology and 100 mm GaN wafer fabrication facility, Nitronex Corp. has developed RF/microwave power transistors for the output stage of 3G wireless base stations. The active device structure consists of a traditional GaN buffer, AlGaN barrier and a thin GaN cap layer (Figure 1). While the thickness and composition of the various layers is still undergoing optimization, the present design delivers RF peak efficiencies in the 65% to 70% range at 2.1GHz, stated Ric Borges, Nitronex's director of device engineering.

As a result, Nitronex is now sampling a 2.14 GHz, 20 W device, the NPT21120. Tested in application board with single carrier WCDMA 3GPP signal, this GaN HFET offers 18.2 W power at 27% efficiency with a gain of 13.6 dB, while achieving an adjacent-channel power ratio (ACPR) of –39 dB (Figure 2). Transistor dies were attached to a high thermally conductive CuW single-ended ceramic package using a AuSi eutectic process. The sources were grounded to the package base through backside vias in the 150 µm-thick silicon wafer. Operating at 28 V, the Idq is 2000 mA. Although, this part is undergoing qualification and full characterization, it is expected to go into production in the third quarter.

Meanwhile, efforts are under way to scale down the gate length for higher-frequency response and implement new masks for improved voltage breakdown. The company hopes to extend the operating voltage to 40 V and beyond. While GaAs HFETs and HBTs share the same high-frequency capabilities as GaN HFETs, their operational voltage, despite recent advances, remains limited to 24 V to 28 V. This limitation is particularly acute in broadband designs, noted Borges.

GaN-on-silicon is also under development at M/A Com with plans to launch products sometime this year. While Nitronex and M/A Com prefer silicon substrate, Cree Research and Eudyna Devices, USA, a joint venture between Fujitsu Compound Semiconductor and Sumitomo Electric Co., have taken the SiC route. At last year's IEDM conference, Fujitsu Laboratories Ltd. of Atsugi, Japan reported a 100 W CW output power for a high gain AlGaN/GaN HEMT fabricated on an n-SiC substrate. Operating at 60 V, it achieves a linear gain of 15.5 dB and power-added efficiency (PAE) of 50% at 2.14 GHz. Unlike others, Freescale Semiconductor is investigating the performance of GaN on silicon, SiC, and sapphire substrates. It is looking at cost and performance trade-offs to provide optimal solutions.

Concurrently, HRL Laboratories LLC in Malibu, Calif. has developed a double heterojunction FET (DHFET) with improved performance over conventional single GaN HFET. According to HRL Lab's paper at IEDM, the DHFET exhibits three orders of magnitude lower subthreshold drain leakage current and almost three orders of magnitude higher buffer isolation than corresponding single HFETs. By comparison to single HFETs, the researcher shows 30% improvement in saturated power density and 10% improvement in PAE at 10 GHz for a GaN DHFET with 0.15 µm conventional T-gate.

Silicon solutions

Meanwhile, for switching applications, advances in CMOS process are pushing silicon into the GaAs turf. Two key players offering CMOS switches include NEC's California Eastern Laboratories and Peregrine Semiconductor. Implementing its proprietary ultrathin-silicon-on-sapphire (UTSi) CMOS or UltraCMOS process, Peregrine Semiconductor has developed RF CMOS switches that have achieved higher speed with lower power consumption. They can deliver insertion loss, isolation, and switching performance that is competitive to switches based on gallium arsenide (GaAs) process technology for GSM handsets.

According to Peregrine's director of marketing, Rodd Novak, UltraCMOS process uses a perfect insulating substrate to overcome RF leakage, isolation and power-handling limitations of standard CMOS to compete with costly pseudomorphic high-electron-mobility transistor (pHEMT) GaAs and other similar complex semiconductor processes. Peregrine's new switches are designed for GSM applications to switch the antenna to the receive or transmit path. For that, it has integrated on-chip functions like driver/decoder, LC filters and protection circuits, thus eliminating the blocking capacitors and the diplexer, normally required with GaAs switches.

Based on 0.5 micron UltraCMOSprocess, Peregrine has unveiled two types of RF CMOS switches. While PE4263 is a single-pole, six-throw (SP6T) CMOS switch for quad-band GSM handset antenna switch module (ASM); the PE4261 is a single-pole, four-throw (SP4T) version in a flip-chip packaging for dual-band GSM handset antenna switch.

On another front, Analog Devices launched an unprecedented monolithic RF variable-gain amplifier/attenuator (VGA) with precise high linearity output power control for wireless infrastructure applications. This single-chip RF VGA, ADL5330, is also the first monolithic VGA to provide broadband operation from 1 MHz to 3 GHz with a precision 60 dB linear-in-dB gain-control range, according to ADI. Unlike

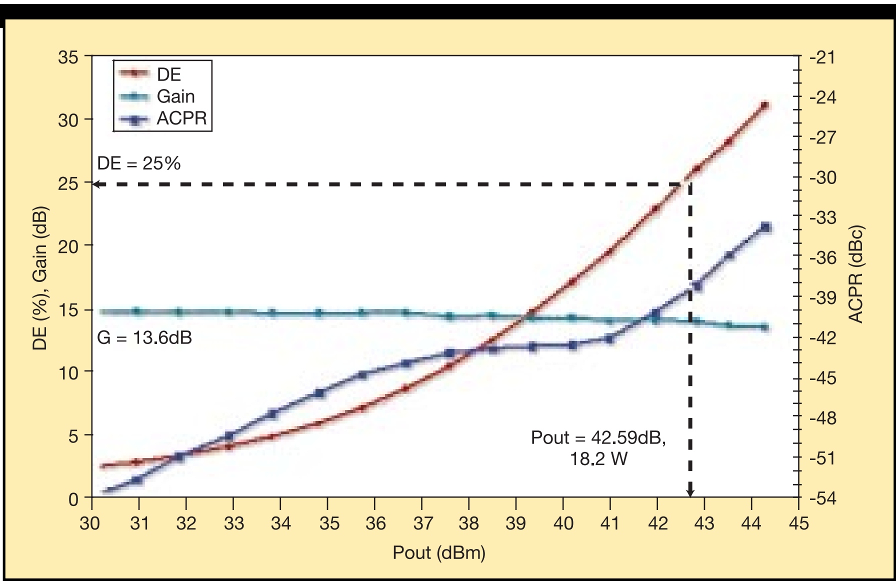

Figure 2. Nitronex's 2.14 GaN HFET, NPT2110, offers 18.2 W power at 25% efficiency with a gain of 13.6 dB.

conventional discrete solutions that require many external components, the single-chip ADL5330 integrates broadband amplifiers and attenuators, offering considerable savings in board area, component count and solution cost as compared to discrete implementations. The precision linear-in-dB control interface further simplifies and eases circuit design. Based on its complementary bipolar (CB) XFCB-2 process, the ADL5330 provides 60 dB dynamic gain and attenuation (approximately +20 dB gain and –40 dB attenuation), an output power level of 22 dBm (1 dB compression point), an output third-order intercept (OIP3) of + 31 dBm at 1 GHz and a noise figure (NF) of 8 dB. The wide dynamic range of the ADL5330, combined with its low distortion and low noise, makes the device an ideal choice for transmit signal paths—at RF and IF frequencies—within wireless infrastructure equipment such as cellular base stations (CDMA, W-CDMA, GSM), point-to-point and point-to-multipoint radio links, satellite equipment, wireless local loop and broadband access services.

Trends in passives

With the advent of WiMax, 3G, ultrawideband (UWB) and other data-intensive standards, the bandwidth, feature, size and cost pressures are constantly increasing. For instance, the ubiquitous cell phones are on a perpetual path of smaller form factor with ever more features. Consequently, designers are seeking miniaturized passive components with higher performance and lower cost, and investigating the possibility of integrating passive components on-chip.

The recently available EIA 0201 surface-mount technology (SMT) size measures 0.060 mm X 0.030 mm and is available in several materials including high-precision silicon or multilayer ceramic. Recently, Murata introduced capacitors in the 01005 size, which is half the size of the of the 0201 package (0.4 x 0.2 x 0.2 mm). Likewise, Vishay's Integrated Products Division is also planning on introducing capacitors in the 01005 small form factor capacitors. Leveraging the precision silicon capacitor's stability over a frequency range (Figure 3) Vishay plans on introducing silicon capacitors in the 01005 package. The capacitance will range from the 0.5 to 12 pF for high-volume manufacturing needs.

Although, direct conversion frequency transceivers minimize the need for filters, optimal RF performance still depends on inductors and capacitors with a high Q. Murata Electronics North America Inc. has a high-frequency inductor series in a 0201-size (0.6 x 0.3-mm) package. The surface-mount film inductors offer a low profile (0.3 mm) and a high Q value in high-frequency bands.

Discrete components are also being developed to support the development and deployment of the UWB technologies in the 3.1 GHz to 5.0 GHz spectrum and other applications in the higher frequency spectrum. Because of the wide bandwidth, new components have been developed to provide balun or filtering devices in standard packaging sizes. Taiyo Yuden recently announced a bandpass filter in EIA 1206 case size. Likewise, exploiting the benefits of LTCC technology, Mini-Circuits has also readied a variety of passive components, including RF transformer, directional coupler and high-pass filter, in 1206 size packages.

While integration can save space, the cost and complexity of integrating digital, analog and RF functions onto a single chip has proved costly and difficult to commercialize. Although, the trend is to integrate all functions onto a single chip, the challenges associated with system-on-a-chip (SoC) is meeting the application needs while still being able to manufacture in a cost-effective manner.

Within the high-density packaging arena or HDP there are demands for smaller and higher precision manufactured passive components. Typically, SIPs are vertically bonded chips using chip scale packaging (CSP) techniques. Passive components are included into SIPs via either an integrated passive device (IPD) or machined components.

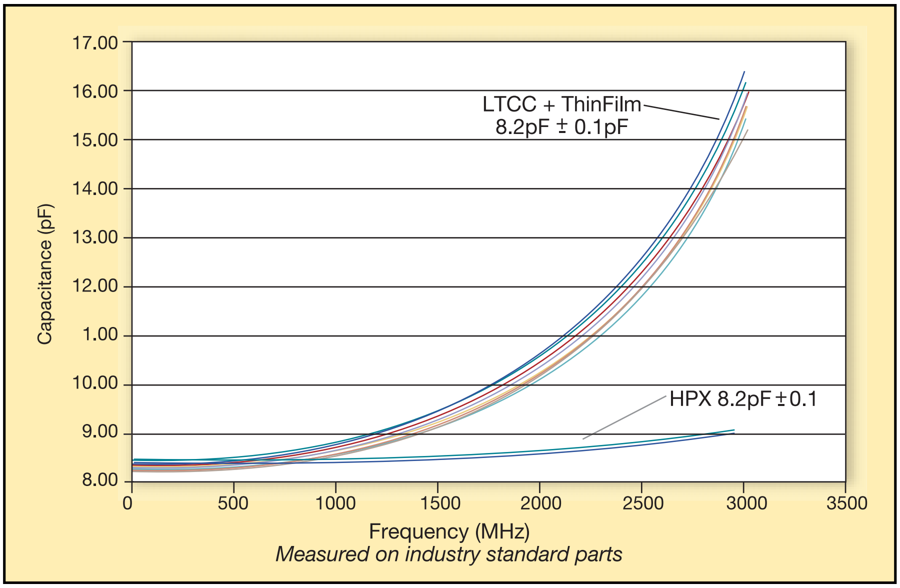

Figure 3. Performance of low temperature, co-fired ceramic (LTCC) vs. discrete high precision capacitor. Courtesy of Vishay Intertechnology.

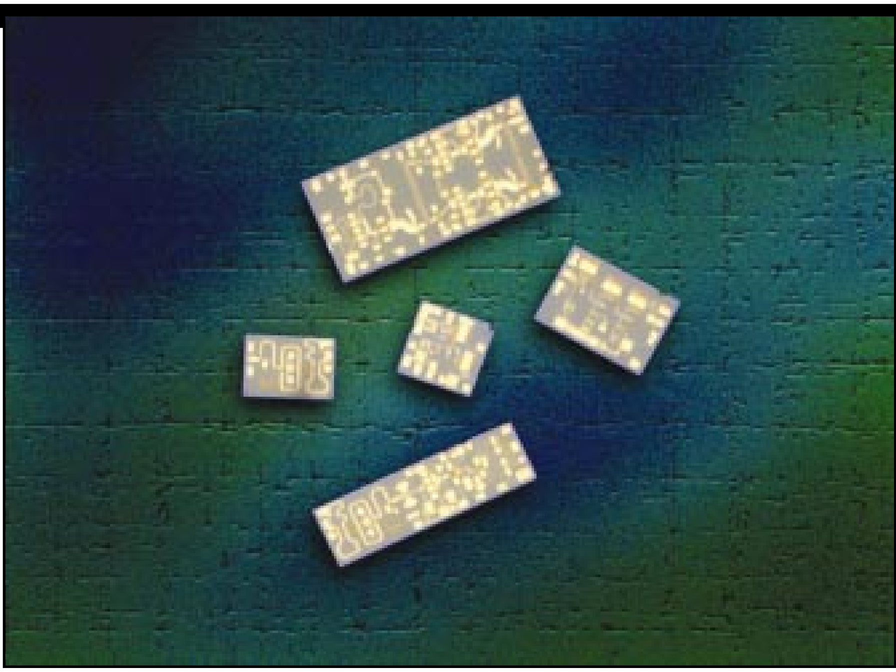

Figure 4. Agilent's newest LNA, AMMC6241, is rated from 26 GHz to 43 GHz with a gain of 20 dB and a noise figure of 2.7 dB.

One of the benefits of IPD is the reduction of parasitic inductance or capacitance, which is needed with higher-speed circuits. Also, chips are operating at increasingly lower voltage levels. However, the noise that is generated by the fast switching speeds is not decreasing in a proportional fashion, even with the reduction in size offered by IPD technology. Hence, there is an additional need to decrease the parasitic inductance through technology. To address this need for reduced inductance, technology developed by X2Y on IPDs includes layers of ground between the electrode and cathode. Because the current directions change as the result of the layered grounds, the overall effective inductance is less than with standard multilayer ceramic chip capacitors (MLCC).

IPDs are also tapping the relatively new technology, namely RF micro-electro-mechanical systems (MEMS). Passive components based on RF-MEMS are becoming increasingly integrated into RF modules. As the bottoms up development of the MEMs building block components matured the production of various passive solutions such as film bulk acoustic resonator (FBAR) by Agilent Technologies is being observed. RF-MEMs are especially well suited for the applications such as switches, capacitors, inductors, resonators and microwave guides. RF MEMs offer performance advantages such as high tuning ratio of MEMs tunable capacitors and high-quality factor of MEMs-based inductors. However, packaging of the MEMS onto microelectronics remains challenging.

Although the RF-MEMS Q factors do not match their discrete counterparts, tunable capacitors have been developed with relatively high Q and tunability. In a recent paper, tunable inductors with Q of 150-500 over a frequency range of 1 GHz to 6 GHz have been developed. The tunability was shown to be 17. Even though static spiral inductors have been integrated into products, tunable inductors are not as well developed as capacitors due to high losses. However, static inductors have reached commercial viability with the available spiral inductors that have quality factors of 55 GHz at 2 GHz and inductance values ranging from 1.5 nH to 15 nH.

Emerging applications

At the upper reaches of the microwave frequency spectrum where millimeter (mm) wavelengths reside—between 30 GHz and 300 GHz—current and emerging applications are in the early stages of creating a demand for monolithic microwave integrated circuits (MMICs) based on gallium arsenide (GaAs) technology. Some portions of the commercial mm-wave band that employ MMICs have been active for a number of years: digital radio transceivers for cellular communications backhaul and ground terminal transceivers for very small aperture terminals (VSATs) are the two major applications. Digital transceivers cover the radio bands from 6 GHz through 42 GHz while most VSATs now operate in the Ku band (12 GHz to 18 GHz) but in the future will be moving higher in frequency to Ka band (26 GHz to 40 GHz). Most of the excitement, however, for the future growth of mm-wave technology lies in recent developments at E-band (60 GHz to 90 GHz).

In October 2003, the Federal Communications Commission (FCC) opened the 70 GHz, 80 GHz and 90 GHz bands for the deployment of broadband mm-wave technologies. Specifically, the commission adopted rules for commercial use of the spectrum in the 71 GHz to 76 GHz, 81 GHz to 86 GHz and 92 GHz to 95 GHz bands. These bands are intended to encourage a range of new products and services including point-to-point wireless local-area networks and broadband Internet access. Point-to-point wireless is a key market for growth since it can replace fiber-optic cable in areas where fiber is too difficult or costly to install. But the real high volume action at mm-wave will likely be in the automotive radar market at 77 GHz. While only available in high-end automobiles at present, cost reductions in MMIC chip manufacturing could lead to significant deployment in all cars in the not too distant future. Such radars will not only be used for collision avoidance and warning, but also for side- and rear-looking sensors for lane changing, backup warning and parking assistance. When this market and others reach full potential in a few years, demand for mm-wave MMICs could increase dramatically from today's rather modest levels.

Because of today's limited applications at frequencies above 30 GHz, the MMIC offerings of many manufacturers are in the early stages of development. When looking through manufacturer's data sheets it is not uncommon to see any number of devices marked as "prototypes" and hence not ready for design use in systems. Nevertheless, products are beginning to arrive on the market. Agilent Technologies, for example, just released a number of second-generation devices in its AMMC series of pHEMT MMICs. The family is intended for point-to-point radio links in microwave base stations. Among the new products being offered is the AMMC 6241, a low-noise amplifier (LNA) rated from 26 GHz to 43 GHz with a gain of 20 dB and a noise figure (NF) of 2.7 dB (Figure 4). Power and driver amplifiers are key elements of all communications systems and two of the new devices in the series are noteworthy: the AMMC 6440 is a 1 W (P1dB of 28 dBm at 42 GHz) power amp and the AMMC 6345 is a driver amp with a P1dB rating of 24 dBm and a gain of 20 dB at 40 GHz.

TriQuint Semiconductor is a company with a variety of recently introduced amplifiers in the mm-wave range. Just last month, three ultrawideband MMICs were released spanning the range from dc to 40 GHz. The TGA4830-EPU offers a P1dB of 11.5 dBm, a gain of 13 and a typical noise figure of 3.2 dB. A medium-power MMIC, the TGA4832-EPU is specified for a P1dB of 18dBm and a 3 dB automatic gain control (AGC) range. Applications include use as a driver for 40 Gb/s optical modulators. The TGA4036-EPU is another medium-power amplifier whose saturated output power is 22 dBm, small-signal gain of 20 dB and 8 dB input/output return loss. Point-to-point and point-to-multipoint communications are typical applications.

Millimeter-wave LNAs with very low noise figures are featured in the product line of Eudyna Devices, USA, a joint venture between Fujitsu Compound Semiconductor and Sumitomo Electric Co. The FMM5703VZ is a packaged device spanning 24 GHz to 32 GHz with a typical noise figure of 2.5 dB and a gain of 17 dB. The FMM5709 is available in two versions: the packaged VZ and in chip form (X). Both cover the 24 GHz to 30 GHz range with the VZ having a noise figure of 3.5 dB and a gain of 21 dB and the X version's noise figure of 2.5 dB and a gain of 23 dB. The VZ is a ball-grid array, surface-mount package

System designers who need a complete MMIC function on a single chip can go to manufacturers such as Mimix Broadband, which recently announced the 29REC029 subharmonic receiver. The highly integrated device incorporates a three-stage balanced LNA followed by an image-reject anti-parallel diode and a local oscillator buffer amplifier. It operates over the 24 GHz to 34 GHz band and is aimed at wireless communication applications such as local multipoint distribution systems (LMDS) and satellite communications. The company also offers LNAs, buffer amps and power amps up to 43 GHz.

With MMICs for automobile radar systems appearing on the horizon, GaAs manufacturers such as United Monolithic Semiconductor are making inroads into the market with devices for short-range radar (24 GHz) and long-range radar (77 GHz). The company, a joint venture between French and German interests, offers a range of automobile radar products such as LNAs, frequency multipliers and mixers that operate in the 76 GHz to 77 GHz band. The CHA1077, for example, is a 77 GHz LNA with a noise figure of 4.5 dB and P1dB power rating of 10 dBm. Two frequency-multiplier devices, the CHU2277/3277, take 38 GHz to 38.5 GHz input frequencies and convert them into 76 GHz to 77 GHz outputs.

Once you get into the upper end of today's working mm-wave spectrum at E-band, product offerings begin to quickly drop off. But Velocium Products recently interjected itself into this market with a number of devices aimed at the 71 GHz to 76 GHz and 81 GHz to 86 GHz communications frequencies and 76 GHz to 77 GHz automotive radar range. Using semiconductor processes obtained from Northrup Grumman Space Technology, the company announced the APH series of HEMT power amplifiers. Now in engineering sampling, the APH 576 is an 81 GHz to 86 GHz power amplifier whose P1dB output power is 20 dBm. The APH 577/578 operates from 83 GHz to 86 GHz with a P1dB power of 18 dBm.

While today's market for mm-wave MMICs trails well behind that of cellular phones, wireless LANs and other applications at the lower end of the GHz frequency spectrum (1 GHz to 5 GHz), the potential for growth in the not too distant future is bright. The key areas for opening up mm-wave technology appear to be in the automotive radar and point-to-point wireless as a last-mile interconnect replacement for fiber-optic cable. RFD

Gene Heftman, freelance writer, also contributed to this report.