Terahertz is Making Waves in the Plastics Sector

By Jan H. Schut

iNOEX's Quantum 360 terahertz device controls pipe wall and layer thickness in foam core PVC and corrugated pipe, which can't be measured by ultrasound gauges in water because of air in the pipe walls. Terahertz is noncontact, so devices don't need to be sized for each pipe diameter. Photo courtesy of iNOEX

Terahertz waves have been exciting researchers in the National Aeronautics and Space Administration and teaching hospitals for 50 years. NASA uses them to measure remnants of energy from the Big Bang and to test materials in the space program. Hospital labs are trying to use them to identify skin cancer cells in minutes instead of days. But practical industrial applications were nearly non-existent until six years ago.

One of the first industrial uses of pulsed terahertz waves was in plastics, so used because of the wave's unique ability to penetrate opaque, shiny, even black plastic, and "see" multiple layers.

The first plastics application was for in-line control of layer thickness in co-extruded polyolefin roofing, installed in November 2011. Later applications include wall thickness measuring in PVC foam core pipe; diameter and thickness measuring in dual-wall corrugated pipe; and control of two densities in coextruded polystyrene foam sheet.

None of these could be measured and controlled by existing devices like nuclear, X-ray, infrared, or ultrasound measurements. Nuclear and X-ray gauges are widely used to calculate total wall thickness but have worker safety issues. Infrared spectroscopy can identify polymers and verify the presence of a barrier layer in co-extrusion but can't measure opaque plastic or differentiate layers of the same material. Ultrasonic waves can verify total pipe wall thickness in a water tank but not if walls have air in them like foam core PVC pipe or dual-wall corrugated. Foam density can be measured by combining nuclear and "laser shadow" gauges but not as precisely as with a single terahertz gauge.

Terahertz––and similar millimeter––wave systems to control thickness, density, and dimensions in plastic extrusion have been a well-kept secret. There are now nearly 60 commercial installations in plastic sheet, film, pipe, and lamination, mostly in the U.S. and Europe. All but one, however, are confidential. The application of the technology for plastics has only been briefly mentioned at major plastics trade shows over the past five years. The technology itself has been written up almost exclusively in photonics and electronics journals.

Meet Teraherz Waves

Electromagnetic waves are measured in length and frequency. Wavelengths are reported in meters, millimeters, micrometers, and nanometers. Frequency is given in hertz where one hertz is one cycle per second. The electromagnetic wave scale goes from radio waves, which can be as long as a kilometer, through micro, millimeter, terahertz, infrared, visible, and ultraviolet light waves to X- and gamma rays, which are the shortest. Millimeter and terahertz waves fall comfortably in the middle between microwave and infrared. In Europe and Japan, terahertz refers to the whole millimeter/terahertz range, while in North America millimeter and terahertz are classified separately.

As electromagnetic waves become shorter, their frequency increases. The spectrum is continuous, so there are no precise beginnings and endings of ranges. They're often defined somewhere in the middle. Microwaves range roughly from 1 meter to 100 mm long with frequencies of 300 megahertz up to 3 gigahertz (300 million to 3 billion cycles per second). Millimeter waves range roughly from 7.5 mm to 3 mm long with frequencies of 40 gigahertz up to 100 gigahertz (40 billion to 100 billion cycles per second). Terahertz waves range roughly from 3 mm to 0.1 mm (or 100 micrometers) long with frequencies of 0.1 to 10 terahertz (100 billion to 10 trillion cycles per second), though most terahertz equipment stops at 3 terahertz. X-rays at the short end of the spectrum are from 10 to 0.01 nanometers long with frequencies of 30 petahertz to 30 exahertz, and gamma rays are even shorter.

Terahertz waves don't damage human cells like UV, X-, and gamma rays, though research done nearly a decade ago at Los Alamos National Laboratory in New Mexico suggests terahertz can alter DNA if the energy is powerful enough. Terahertz waves can be directed like light to produce visual images and transmitted short distances like radio waves. Most significant to plastic applications, terahertz waves reflect, pass through, or are absorbed differently by various substances, so they can be used to identify materials and measure wall and layer thickness without contact. Noncontact measuring means terahertz devices don't have to be sized for a particular pipe diameter like ultrasound. Until six years ago, terahertz devices were commercial only for aerospace, medical, and R&D applications because the sensors were so expensive.

There are two types of millimeter and terahertz wave devices: those that emit a steady continuous energy stream with narrow frequency in the millimeter or terahertz range, used primarily for imaging, and those that emit a continuous stream of ultra-short pulses, used for both imaging and thickness measuring. Pulsed signals for thickness control measure time intervals as signals pass through or reflect off surfaces or layer interfaces. Pulsed millimeter and terahertz devices include "photoconductive switches" driven by an ultra-short pulse laser and "Cherenkov sources" driven by a much higher power, ultra-short-pulse laser, shining through a nonlinear crystal (lithium niobate). Both operate at room temperature.

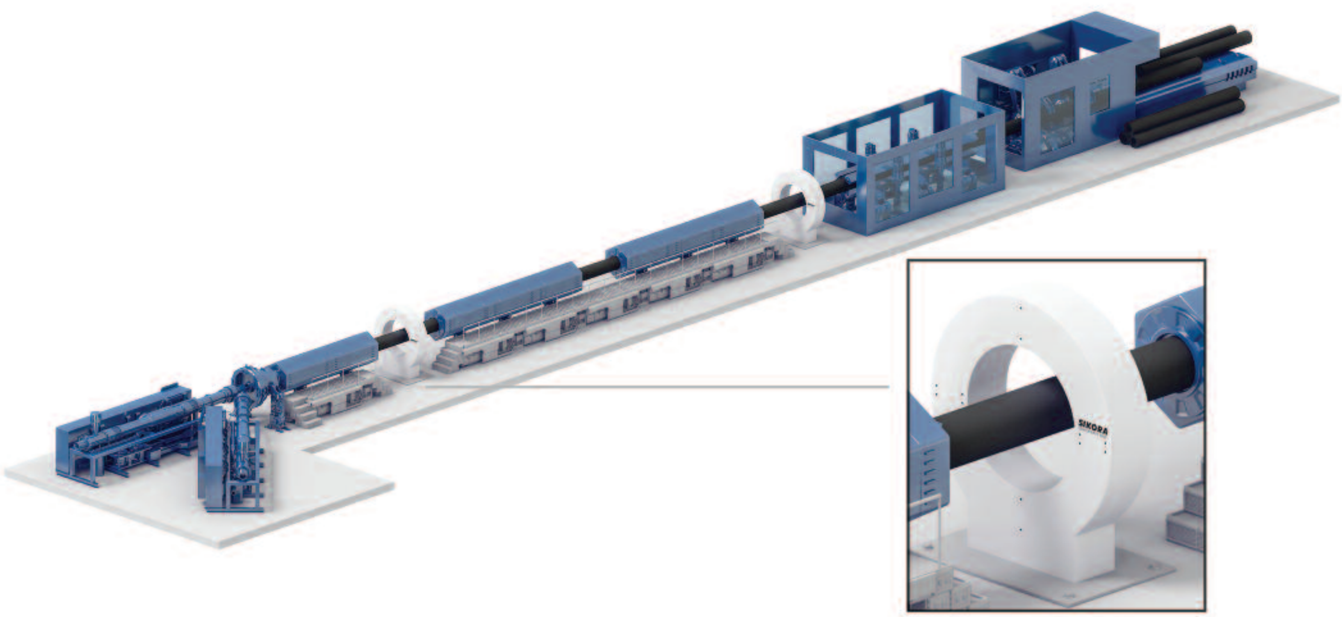
Pulsed terahertz waves can measure plastic walls up to 6 inches thick, depending on polymer and filler, but they can't measure very thin layers. "In a monolayer sheet we can measure down to 12 microns, but in a multi-layer stack the thinnest layer we can measure is approximately 50 microns," notes Irl Duling, director of business development at TeraMetrix LLC of Ann Arbor, Mich.

TeraMetrix, formerly Picometrix, is the oldest maker of pulsed industrial terahertz devices. It was founded in 1992. Millimeter waves, which are longer than terahertz, can penetrate even thicker walls because of a longer wavelength. However, they are lower bandwidth, so they are less precise than terahertz. Both wavelengths can also check concentricity and diameter in pipe, but terahertz measures smaller pipe diameters, while millimeter waves measure larger diameters.

First Industrial Teraherz Sensors in Plastics

At least five makers of control instruments offer pulsed terahertz devices for plastic thickness measuring, some for sheet and film, some for pipe. Some build the sensors, some specialize in installations and develop software.

TeraMetrix, a division of LUNA Innovations Inc., uses technology designed by Bell Labs with a proprietary semiconductor and patented fiber coupling. The company makes its low-temperature-grown indium gallium arsenide (InGaAs) semiconductor



Sikora offers a new millimeter wave thickness measuring device called Centerwave 6000 in five sizes for pipe from 90 mm to 3.2 meters in diameter. Its first millimeter device was sold in May to control wall thickness of monolayer sheet; the second will control monolayer pipe. Photo courtesy of Sikora material in-house and shines a short-pulse laser into the semiconductor, which has a small antenna on top to produce terahertz waves.

TeraMetrix (formerly Picometrix) claims to have built the world's first commercial terahertz wave system in 1999 for university research and development. It was called the T-Ray 2000.

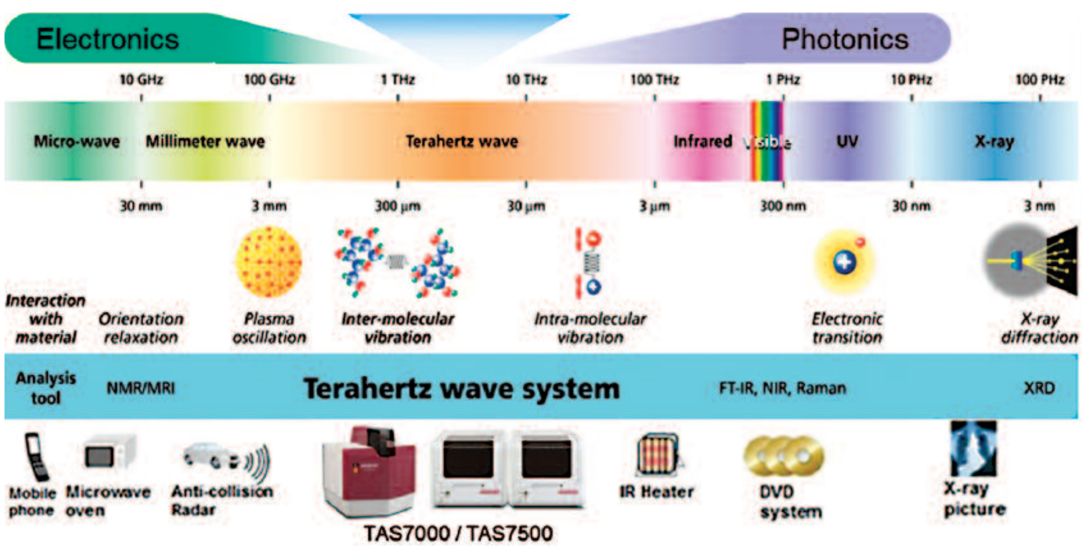
The company developed the QA-1000 in 2004 for NASA to control the adherence of foam insulation sprayed onto liquid hydrogen fuel tanks for space shuttles. In 2007, Picometrix introduced its T-Ray 4000 control unit, the first industrial terahertz device with a short pulse fiber laser, which was used by NASA to measure things like corrosion, delamination, and coating thickness in the space program.

In November 2011, Automation and Control Technology Inc. (ACT) of Dublin, Ohio, integrated a T-Ray 4000 terahertz sensor from Picometrix into a coextruded sheet line in the U.S. making 10- to12-foot wide thermoplastic polyolefin roofing in 100-foot rolls. This is believed to be the first mainstream industrial application of terahertz in plastics and possibly the first anywhere. The sensor scans back and forth to measure and control the thickness of a top virgin white layer co-extruded over a fabric scrim while a gray regrind layer is extruded on the back. Both layers are measured by one terahertz sensor, but only the top layer is automatically controlled by ACT's software with die control of 1-inch zones. The bottom layer is controlled manually. ACT's system reportedly reduces overall thickness deviation to less than +/- 0.6 mils.

In 2012, Picometrix introduced a hand-held thickness measuring device called single-point gauge,which measures one point on a plastic wall at a time, and a T-Ray 5000 solid-state, photoconductive switch type terahertz sensor. T-Ray 5000 is the first terahertz system that is CE UL qualified for an industrial environment. ACT also installed the first T-Ray 5000 that year on a co-ex EPDM sheet line measuring layer thickness and density with a single sensor.

Recently, ACT installed terahertz sensors on coextruded polystyrene foam sheet lines for cups in Michigan and Pennsylvania to control two foam layers of different density. The sheet is formed as a horizontal bubble and slit in two, so two sensors are needed. Foam sheet is then cut into strips the height of the cup, the lip is rolled, and the bottom welded on. In February 2017 Indev Gauging Systems Inc. (indevsystems.com), a unit of Jasch Industries Ltd. in India, acquired the assets of ACT, and the combined company now does business as Indev-ACT (www.indev-ACT.com). David Pond, president of Indev-ACT, says it has installed 20 Envision Terahertz thickness measuring systems on plastic sheet, film, foam, and coating lines, all in the U.S.

Thermo Fisher Scientific Inc. partnered with Picometrix in 2012 to incorporate its terahertz device into Thermo Scientific's web gauging and measurement control platforms. Thermo Fisher, headquartered in Erlangen, Germany, first showed the technology at the K Show in 2013 and has 15 installations in extruded plastics, foam, and laminated building products. Its Thermo Scientific Terahertz Sensor provides noncontact single layer or multilayer thickness



Terahertz waves reflect, pass through, or are absorbed differently by different plastics, so they can measure layers inside a plastic wall without contact. A pulsed terahertz signal returns from layered surfaces, is reflected onto a sensor, and interpreted by software to measure layer thickness.

Image courtesy of SKZ

measurement of calendered, laminated, or coextruded material and can "simultaneously measure total thickness, basis weight, and density, and detect delamination with one sensor," Thermo Fisher says.

iNOEX GmbH of Melle, Germany, developed the first terahertz system for pipe, called Quantum 360, using commercially available pulsed terahertz sensors and proprietary software to control wall thickness in foam core PVC and corrugated polyethylene and polypropylene pipe. Quantum 360 was developed with SKZ, formerly Sud-Deutsche Kunststoff-Zentrum, Germany's largest plastics institute, and also introduced at K 2013 in Germany.

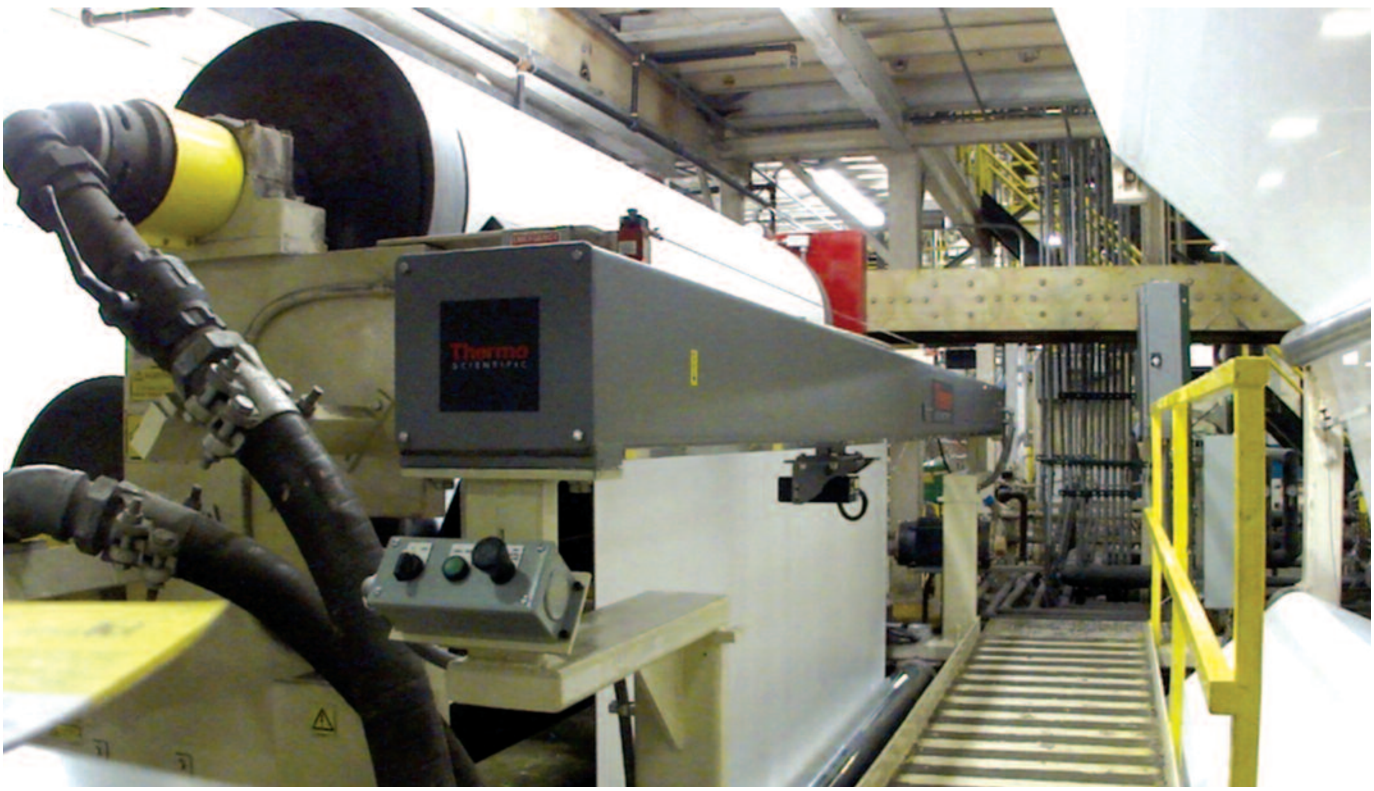
iNOEX's patent application WO 201574642 claims a preferable frequency range from 0.1 to 10 terahertz with a high energy efficiency/wave output ratio of 1/100 with no cooling needed. A temperature change of 10˚C in the terahertz device reportedly makes a deviation of only 0.001 mm in measured wall thickness.

Quantum 360 comes in four sizes for pipe diameters of 10 to 250 mm; 63 to 400 mm; 250 to 1,000 mm, and 250 to 1,200 mm, all for wall thicknesses from 100 microns to 60 mm. iNOEX says 10 systems are installed commercially to control smooth and foam-core pipe, mostly in Europe. The first Quantum 360 pipe system for corrugated pipe was installed in the U.S. in 2015.

"The difficulty is that we have to reverse around the pipe and also move at line speed with the pipe to measure the circumference of one crown and valley," says iNOEX marketing director Arno Neumeister.

One corrugated pipe client previously took a destructive test sample every hour to be sure the pipe was in spec, but now only does a destructive test once a day, iNOEX says.

Two German laser makers also build pulsed terahertz sensors, which are used by research institutes and universities: Menlo Systems GmbH in Planegg and Toptica Photonics AG in Graefelfing. Toptica offers an industrial pulsed terahertz device intended for plastic thickness control, which Toptica says can resolve plastic layers down to 10 to 20 microns depending on polymer. But there are no known industrial installations in plastics.



Picometrix built the first commercial terahertz device, T-Ray 2000, in 1999 for university R&D and the first industrial terahertz device with CE UL certification, T-Ray 5000, in 2012. The T-Ray 5000 is shown here controlling layer thickness on co-ex TPO roofing. Photo courtesy of Picometrix

First Millimeter Sensors for Plastics

At the K 2016 show in Germany last October, four companies introduced what are believed to be the first commercial millimeter wave thickness gauges for plastics. iNOEX launched its WARP 100 and WARP Portable millimeter wave sensors to control large diameter pipe, using solid-state, chip-like transceivers built in-house. WARP 100 uses 19 fixed transceivers distributed around the pipe circumference to measure 100 percent wall and layer thickness with a minimum wall thickness of 5 mm. It also controls diameter, ovality, and eccentricity. WARP 100 can measure up to 150 mm diameter multilayer polyethylene pressure pipes and 100 mm diameter PVC pipe, depending on the compound and level of filler, which absorbs energy. iNOEX has installed 10 WARP 100s, and sold 50 WARP Portable handheld thickness measuring devices in three months since they began shipping in June.

Sikora AG of Bremen, Germany, introduced its Centerwave 6000 millimeter wave device to measure wall thickness, diameter, and ovality of plastic pipes with a frequency range of 80 to 300 gigahertz. The technology, for which the company has applied for a patent (WO Pat. # 2016139155), was developed with the Fraunhofer Institut fur Hochfrequenzphysik und Radartechnik in Wachtberg, Germany, and the SKZ. Sikora sold its first system in May 2017 for 2.5 meter-wide, monolayer sheet with thickness of 3.8 to 25 mm. The first pipe system was installed in the second half of 2017 for mono-layer pipe with an outer diameter of 630 mm. Sikora offers five systems for smooth monolayer pipe from 90 mm to 3.2 meters in diameter. They use either one or two constantly rotating transceivers for 360-degree thickness measuring or two static transceivers measuring four points of the pipe circumference. Sikora also says it's developing a terahertz system to measure thinner walls, as well as software to measure layers in multilayer pipe.

Sysmetric Ltd. of Afula, Israel, a maker of material handling and feeding systems for plastics, introduced a millimeter wave device to control total wall thickness for plastic pipe using a commercial millimeter device with a frequency of around 60 gigahertz. Sysmetric, founded in 2003, has installed "less than a half dozen" millimeter sensors for pipe thickness control, all in Israel, and expects to offer them outside of Israel late this year.

Hammer-IMS nv in Hasselt, Belgium, a spinoff of Belgium's Catholic University of Leuven, launched its new M-Ray millimeter wave sensor to control sheet thickness and already has two M-Ray systems installed commercially. The first is at ANL Plastics nv in Wellen, Belgium, where Hammer's Marveloc 602-Curtain with four M-Ray sensors controls thickness and density of PET sheet for thermoformed packaging. ANL was featured in the German magazine *Coating and Converting* in July 2017, becoming the first and only company globally to go public about using terahertz- or millimeter-gauge control. Hammer's second installation controls a non-woven product in France.

Hammer builds the device by mounting multiple millimeter-wave heads at fixed positions on a solid frame. The entire frame scans back and forth in the transverse direction to guarantee high measurement coverage. The M-Ray sensor uses 10 to 1 mm waves at 30 to 100 gigahertz frequency. General manager and co-founder Noel Deferm says they chose millimeter waves rather than terahertz "for cost and scalability because we can generate, control and steer millimeter waves with electronic circuitry, which we create, whereas shorter terahertz waves need optical light components to control them, and that adds cost."

Paint and Other Layer Control in R&D

IMD Ltd. of Bruegg, Switzerland, introduced an off-line terahertz test device at K 2016 to check layer thickness in coex bottles and preforms. The first generation used a photoconductive switch device built by TeTechS Inc. of Waterloo, Ont., but was taken off the market. IMD's second-generation test device uses an industrial terahertz sensor from another supplier and can reportedly analyze layers in more complex bottle shapes. IMD plans to relaunch the device in 2018.

Three companies are developing pulsed terahertz devices to control the thickness of automotive paint layers, but none are believed close to commercial. Helmut Fischer GmbH, headquartered in Sindelfingen, Germany, and the Fraunhofer-Institut fur Technno- und Wirtschaftsmathematik in Kaiserslautern, Germany, are integrating terahertz for automotive paint control, and presented the technology at a coating conference in Germany this year. ABB Switzerland Ltd. of Baden-Daettwil, Switzerland, is adapting terahertz to robotics for automotive painting. ABB presented its findings in Cancun at IRMMW-THz 2017, a 40-plus year-old conference on infrared, millimeter and terahertz research. IMRA America Inc. of Ann Arbor, Mich., a laser company, supplied pulsed lasers for "Cherenkov" crystal devices to control automotive paint layer thickness in Japan based on technology from Nagoya University.

In other non-plastic thickness measuring applications, Tokyo-based Advantest Corp. developed a pulsed TS 9000 MTA terahertz system for thickness measuring in semi-conductor chip production, which Advantest says is the only commercial system in chip production. Advantest. TeraView Ltd. of Cambridge, U.K., and TeraSense Group Inc. of San Jose, Calif., also offer pulsed terahertz devices for medical imaging. There are also pulsed terahertz research groups at the Fraunhofer Heinrich-Hertz Institute in Berlin and at Osaka University in Japan.

Continuous terahertz and millimeter wave devices, used only for imaging, are very different––and less expensive––than pulsed devices. Continuous waves are generated by electronic devices like radar, vacuum devices like "backward wave oscillators," "quantum cascade" lasers, which are specialized semiconductors that need cryogenic cooling, and "photo mixing," which combines different laser lengths on an antenna.

Makers of continuous terahertz imaging devices include Huebner GmbH of Kassel, Germany, TeraView, and TeraSense. These types of devices are used for scanning packages and envelopes for dangerous contents. Makers of continuous millimeter devices for imaging include L3 Technologies in New York City, which makes airport security scanning booths for passengers.

ABOUT THE AUTHOR

Jan Schut is a former senior editor at *Plastics Technology* magazine, who has written about plastics for nearly 30 years, covering recycling, extrusion, blow molding, injection molding, and developments in polyolefins and biopolymers. She also has been writing a new-technology blog for SPE (www.plasticsengineeringblog.com) since 2009. Contact her at bragi.schut@verizon.net.