Integrated Circuits for Millimeter Waves

by David Rutledge

RADIATION IS CHARACTERIZED by its wavelength and frequency. Millimeter waves have a wavelength in the range between a millimeter, surprisingly enough, and a centimeter — fingernail size or smaller. (The submillimeter range goes from 100 microns up to a millimeter.) In the electromagnetic spectrum, the band lies between microwaves, which are longer, and infrared radiation, which comprises the shorter wavelengths. As for frequency, the millimeter waves go from 30 gigahertz to 300 gigahertz, and the submillimeter range from 300 gigahertz up to 3 terahertz. Microwaves have lower and infrared radiation higher frequencies.

The characteristics of different kinds of radiation enable us to use them to "see" different things. For example, one of the most successful uses of millimeter waves so far is in looking at the electron density and the magnetic field inside a tokamak, a device for generating a fusion reaction in a plasma (ionized gas). Microwave radiation won't work in this application because it bends in a plasma, making it difficult to tell where the microwave beam went or where it's going. And infrared systems are strongly affected by vibration; tokamaks, when they create a plasma, fire a large current pulse that tends to rattle everything. Millimeter and submillimeter waves, however, are just right.

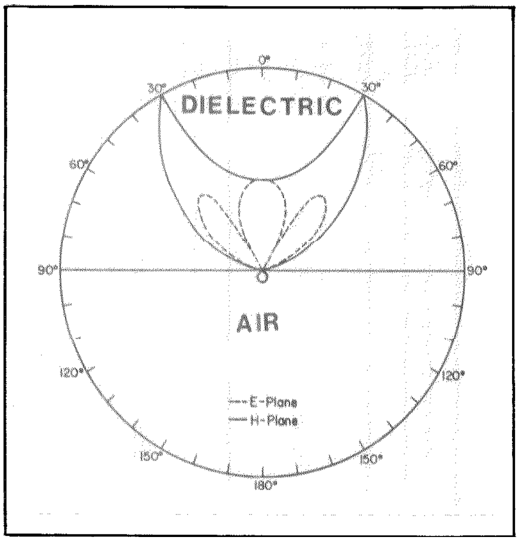
Systems using millimeter waves offer a number of advantages. They can have a higher resolution than microwave radars, and the millimeter waves penetrate smoke and dust much better than infrared systems do. This feature of millimeter radiation has suggested, especially to the military, potential applications in imaging radar and missile guidance. Several such systems have already been developed.

Astronomy is the most difficult application. Objects that are very cold (in the range 10K to 50K) radiate at millimeter wavelengths. With millimeter wave astronomy scientists can see the formation of stars in large, cool, gas clouds. There's also an active effort at Caltech's Jet Propulsion Laboratory to use millimeter wavelengths to study the chemistry of the earth's upper atmosphere, which is also very cold.

The major stumbling block in all these applications is the technology. In some ways it's competitive, but in other ways, particularly in costs, it's not. Infrared systems, which usually use natural radiation as a source of power, may be the best bargain of all. At microwave wavelengths, for a source of 100 mW of power, if you know how to design an oscillator, you can go buy a $10 transistor, wire it up, and you're in business. At millimeter wavelengths, you can't just wire it up unless you're very skilled, but even if you are, the transistor doesn't exist anyway. The device you could use, if you want, say, an FM modulated source, is called a carcinotron. Despite its name it doesn't cause cancer, but its price of $100,000 is enough to make anyone feel bad. And it lives for only about 500 hours — a good deal for the manufacturer but not for the student working in the lab.

Detectors present similar problems. You can buy a good $10 Schottky diode detector for microwaves and wire it up yourself. Similarly, at infrared wavelengths the photoconductors are reasonably priced. But assembling a millimeter-wave system is, again, very difficult and probably would require a complete $10,000 receiver.

You also need to be able to transport energy around within a system. Most



This polar plot shows antenna sensitivity at different angles in the two principal planes. The antenna is much more sensitive to power coming from the dielectric than from the air side.

modern microwave systems depend on integrated circuits that are quite reliable and reasonably priced. Infrared technology of lenses and fibers has been developed successfully. With millimeter waves, however, we've been stuck with tiny, hollow metal waveguides. The hollow metal guides become even smaller and harder to make as the wavelength gets smaller. There are only a couple of machinists in the country who can make these things; it often takes a year of waiting and can cost $1,000 per joint for the connections in a millimeter-wave system at the higher frequencies.

About five years ago several research groups, including mine, came up with the idea that integrated circuits that would work at millimeter wavelengths could solve these technological problems and make millimeter waves a more useful resource. For example, we could try to make an imaging system with antennas, diodes, and processing circuitry on the same circuit. Such a system would be small, light, rugged, and much cheaper than previous approaches. Perhaps a complete radar system could be built on a chip that would include everything: thin film, metal antennas, transistors, diodes, receive circuits, and processing circuits.

The work of my own group (which includes former grad student Dean Neikirk, now assistant professor at the University of Texas, and Professor Neville Luhmann at UCLA) has concentrated on three parts of the problem. We've developed antennas that work on a dielectric substrate, such as quartz, or a semiconductor substrate, such as silicon or gallium arsenide. We've also made some bolometer (thermal) detectors that work with the antennas and have built arrays of antennas and bolometers that can make pictures of plasmas.

First we dealt with the antenna problem. Antennas on a substrate behave very differently from antennas in free space. They're primarily sensitive to radiation that comes from the bottom side of the substrate *through* the quartz or the silicon. This wasn't the obvious direction to expect, and when scientists began testing such antennas, this isn't where they looked. Antennas are also strongly affected by substrate modes — waves that bounce around inside the substrate. While these same modes are responsible for the success of optical fibers, they're a real problem for millimeter waves.

To get an idea of what causes the antenna to be more sensitive to radiation from the substrate, we can think of it as a small dipole antenna that's receiving power. Let's assume it's lying on a quartz (or silicon or gallium arsenide) substrate, and a wave comes in that is incident on the antenna. The antenna responds to the wave's electric field in the sense that the field that's left over is the sum of the wave that comes in and the wave that bounces off — the incident wave and the reflected wave.

When you go through the mathematics, it turns out that when the wave comes from the top, or the air side, the reflected wave has the electric field pointed in the opposite direction. Because of a phase change, the reflected wave tends to cancel the incident wave, making the leftover field small, and the antenna responds weakly. In a wave coming from the dielectric, or substrate, side, the electric field is modified by the dielectric, and the opposite situation occurs. The electric field and the reflected wave have the same sign as the incident wave, resulting in a big field and a strong antenna response. So it's obvious that you need to focus power in from a lens on the back side of the substrate.

Not only does this enable us to come in from the side where the antenna is most sensitive, it also deals with the problem of the substrate modes. One way to understand this problem is to think of the antenna as on top of a substrate transmitting rays of energy to propagate out. There is a particular angle, known as the critical angle, where all the energy at larger angles is completely reflected. This is what makes optical fibers work — the light just bounces around inside the substrate.

But this is inefficient for a transmitting antenna, since 80 percent of the energy may be lost to power that's just bouncing around inside. With the lens on the back of the substrate, however, waves coming out from the antenna hit the curved surface at a small angle of incidence. So the reflection is small, and the radiation goes right through.

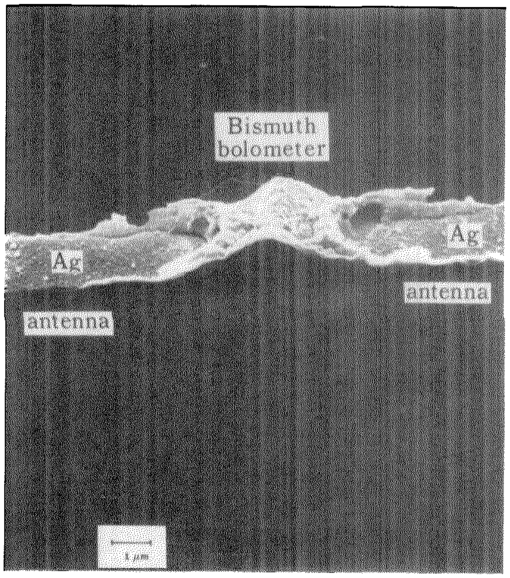
The antennas we use for most of the circuits are shaped like bow ties turned on their sides. The detector is at the apex of the bow, and we can think of the wings of the bow as collecting the energy and putting it down into the diode. Because there aren't any good computer models of the antennas, we design them by first making large microwave models. We model at longer wavelengths (say, 30 mm) where we can cut the metal shapes out quickly with scissors and try a large number of shapes to see how they work. The successful ones can then be made in smaller sizes; for example, the integrated circuits that we built had a wavelength of 1 mm.

Making a detector that would work with the antennas was the next problem. We developed a variety of thermal detectors called bolometers, which are temperature-sensitive resistors. The resistor will absorb power and heat up, and the power can be measured by the rise in temperature of the bolometer. A good thermal detector makes it hard for the heat to get out, so that the temperature rise will be larger and more easily detected. Our bolometers, which are made of bismuth, can detect a power of about 10 picowatts (10^{-11} watts). They can detect a change in about a microsecond — fairly fast for thermal devices.

Dean Neikirk came up with an ingenious idea for preventing heat from escaping from the bolometers. Using a photosensitive material called photoresist, a standard material for making integrated circuits, he developed a quite unstandard procedure. His idea was to get the bismuth resistor to go up in the air a little bit to keep the heat from getting out into the substrate. He did this with a pattern of little bridges, first of silver, then bismuth, finally arriving at a structure where the silver is left with bismuth on top of it, so that the bismuth can pick itself up off the substrate about ½ to 1 micron and then come back down. It's a very sensitive device; for each microwatt of power received the temperature of the bolometer rises about 1 degree. It's also fragile; a lot of power will burn it up.

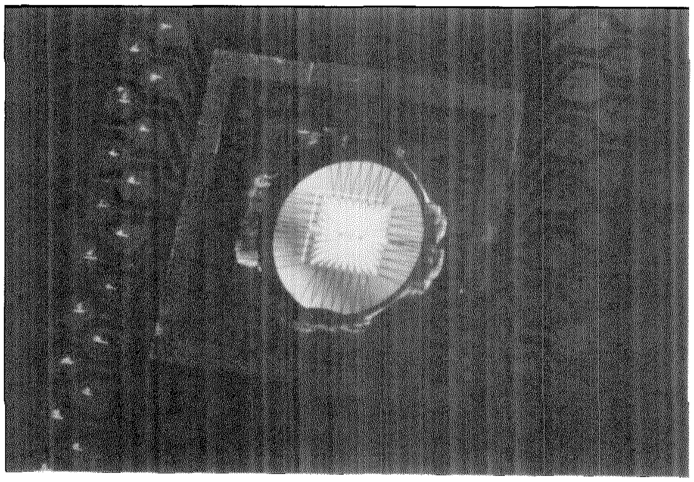
When we had worked out both the antennas and the detectors, we combined them into imaging arrays to look at plasmas. Conventional imaging at millimeter wave frequencies has been done with one detector (partly because they're so expensive) and the optics moved around to point at different areas in order to make the image. But when things are happening fast, as they do in plasmas, you don't have time to move the mirrors around to see the different parts. In our arrays each antenna has its *own* detector, and once we measure the power at each antenna, we can plot it out and get an image.

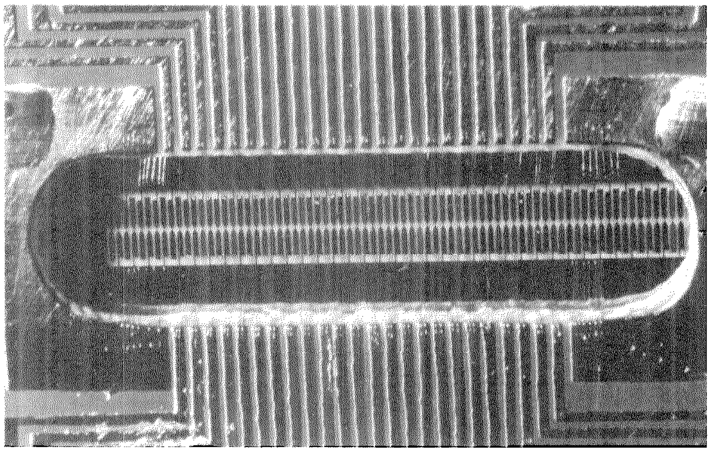
The main design question for such an imaging array is how far apart to put the antennas. If you put them too close together you need a lot of extra electronics; if you put



The air-bridge, bismuth detector (left), seen through a microscope, lifts to keep heat from escaping into the substrate. The silver antenna, which shorts out the bismuth, is a couple of microns across and several microns long.

Below *is an imaging array for 0.1 mm wavelengths. The 40 bow-tie antennas occupy the middle of the circuit — about 1 mm across.*





The antennas above are the narrow vertical metal strips, spaced about ¼ mm apart. This is an imaging array for a wavelength of 1 mm for tokamak measurements.

them too far apart, you may miss some of the picture. This is just a sampling problem, fortunately the sort of problem that's common in electrical engineering, and there are criteria we can use to determine how close together the antennas should be. It turns out that for most of our systems, the antenna spacing should be about half the wavelength in the lens.

We have already set up our imaging arrays on a tokamak and have made some initial plasma measurements. We've gotten some good first images out of the system and expect the array to be of use when experimental changes are made in the tokamak — to be able to tell what the plasma is doing and even where it is, which has been difficult to determine before.

We've developed other arrays that we haven't yet applied to real- life measurements. There is one for a smaller wavelength — about .1 mm. The antennas get smaller as the wavelength gets smaller, ending up in this case looking like mere fuzz on the chip. The bow tie antennas are not much bigger than the detector. We've also made a two-dimensional array of antennas (bow ties with detectors that form rows and columns) that can follow point sources around rather than provide an image. We can look for the largest signal on a particular row and column, and this will tell us where the source is in the far field.

Still another array, which will soon be applied to plasma measurements, is basically a polarimeter: It tells us which way the electric field is pointing. There are two sets of bow ties in this array — one set alternating with another set pointing at right angles to it. This arrangement effectively creates two imaging arrays — one leans to the right and responds to the electric field pointed toward it, and the other leans to the left and responds to the other component. When we take all the measurements and compute a bit, we can determine which way the electric field is pointed at any particular place. This can be important in radar applications, because you can often tell from the polarization characteristics of the target whether it's manmade or natural; manmade targets tend to have more smooth surfaces that preserve the polarization.

In a plasma this can be applied to the magnetic field. The magnetic field in a plasma vessel, such as a tokamak, causes the electric field to turn a little bit. If you can measure how far the electric field is turned, then you can figure out how big the magnetic field is. This is a crucial item because the magnetic field is what holds the plasma together.

It's important in a millimeter-wave system to have an array that delivers the full resolution allowed by the optics, because, while the resolution of the millimeter-wave systems is better than that of microwaves because the wavelengths are smaller, it's also obviously worse than infrared. Tests on our imaging system have shown that the array itself is not limiting what we can see, but that we are diffraction limited.

Given the progress we've made so far in making antennas and detectors and combining these in imaging arrays, it should be possible to make integrated circuits that also include processing circuits and that act as complete millimeter-wave circuits. And if transistors can be made fast enough to work at millimeter wavelengths, we should be able to make small, inexpensive radar with receiver and oscillator on a single chip as well.

In the future our work will concentrate on improving these arrays. One of the obvious ways is to put more sensitive detectors in them. Over the last year we've been working to incorporate Schottky diodes, which are more sensitive detectors than bolometers but much harder to make. We think this will provide the sensitivity necessary for military applications. Tom Phillips, professor of physics, and others have developed a superconducting tunnel detector, which is even more sensitive than Schottky diodes. This detector might make possible an array sensitive enough to use for millimeter-wave astronomy. □