MILLIMETER WAVE TRENDS FOR THE '80's

James C. Wiltse
Engineering Experiment Station
Georgia Tech, Atlanta, GA 30332

ABSTRACT

Millimeter-wave activity has been increasing for the past several years, motivated by technology advances and an increased need for sensors capable of operating in adverse environments (smoke, fog, dust, rain) or making special remote measurements. Numerous applications are being investigated, but those involving missile guidance, target acquisition and tracking, and remote sensing appear to be providing the greatest impetus. Major measurement programs have been initiated to obtain better characterization of propagation effects (attenuation, backscatter), ground or sea clutter, multipath effects, and target signatures at both millimeter and submillimeter wavelengths.

The presentation will briefly summarize the state of the art in components, sources, and receivers, and discuss the measurement programs mentioned above. From this basis, the more important current applications will be described in some detail. A projection of possible future applications will also be given.

Introduction

The past several years have seen a strong revival of research and applications in the millimeter-wave region, with related investigations extending into the submillimeter-wave range as well. A number of factors have contributed to the renewed activity; these include the advent of new technology (such as better sources and lower-noise mixers), the evolution of new requirements for sensors (mostly by the Government for missile guidance, target acquisition and tracking, and remote sensing), and the general superiority of millimeter-wave systems over optical and IR systems for penetration of adverse environments (smoke, fog, haze, dust, and rain).

For low power applications (watts of peak power; milliwatts average) solid state IMPATTS have seen extensive development and now operate well above 200 GHz. Gunn oscillators are now available to 100 GHz,[1,2] klystrons to 200 GHz, and carcinotrons to 300 GHz.[3] In medium power tubes, the magnetron has been improved in lifetime and is available to 95 GHz, and the extended interaction oscillator (EIO) has appeared and is in use up to 140 GHz.[4] The gyrotron tube, which has achieved very high-power levels (megawatts peak) at efficiencies greater than 30%, has already seen application to fusion research and undoubtedly will soon see use in radars.[5] Laser-pumped lasers can also be used to produce significant power (up to tens of kilowatts peak) at specific millimeter and submillimeter frequencies.[6]

Component development has also progressed recently;[1,2] in particular integrated circuits, image lines, and quasi-optical techniques have been developed.[7,8,9] One of the most significant areas of improvement is in low-noise Schottky mixer diodes,[10] and this has led to better receivers for radar, communications, radiometry, and radio astronomy.

The recent growth in millimeter-wave activity is certainly attributable in part to the availability of improved components, particularly solid state sources. While such sources provide relatively low power, they are smaller in overall size and require much lower voltages (and prime power) than vacuum tube types, such as magnetrons and klystrons. Over the past half-dozen years solid state sources have been improved in several ways, such as availability of higher power out puts and operation at higher frequencies. Some of the improvements are more subtle, but very important for systems; these include development of injection-locked IMPATT amplifiers, frequency-doubled Gunn oscillators, and frequency stabilized or phase-locked sources. These types of improvements are permitting the extension of all-solid-state pulse-compression and coherent MTI (moving target indication) radars to as high as 94 GHz. Similarly, all-solid-state passive radiometers are being extended to at least 140 GHz.

In general, atmospheric propagation effects dominate considerations relating to applications. This is true even for satellite applications outside the atmosphere, since frequencies may be chosen for which the atmosphere is opaque in order to provide covert operation. Typical values of atmospheric attenuation have been well-established for frequencies up to 100 GHz, including the attenuation and backscatter due to rain or fog, and programs have now been initiated to obtain better information about atmospheric effects and effects of smoke or dust above 100 GHz. Of particular interest are effects in the atmospheric "windows", or attenuation minima, at 35, 94, 140, and 220 GHz. Reflectivities of land and sea (i.e., "clutter"), as well as targets, are also being obtained at these frequencies.[11]

Applications

One of the areas of greatest activity in millimeter waves is that of guidance for missiles and projectiles.[12] Present precision guided weapons are based upon the use of TV or laser seekers; however, they are not adverse weather systems (and mostly daytime-only types). What is needed in general is a precision tracking or weapon guidance capability that will perform satisfactorily in smoke, fog, dust, or rain, day or night.

The Defense Advanced Research Projects Agency and the three Services are now placing particular emphasis on terminal guidance of tactical air-to-surface missiles. Antennas for such "terminal seekers" are aperture limited to less than 6 or 8 inches. In order to obtain narrow beamwidths from such small antennas, millimeter-wave frequencies are being used, with the choice typically being 35 or 94 GHz. Extensive design and measurement programs are underway to develop seekers optimized for various military requirements.[13]

In general, all-solid state design has been emphasized for these seekers, consistent with the need for small size and low voltage. Although transmitter output power is low, it is sufficient because the range needed is short. In addition to active (radar) seekers, passive radiometric systems are also being investigated. Even combined active-passive systems are in use, wherein an active seeker may switch over to a passive radiometric sensor near the end of missile flight, since the radiometer does not have the problem of aimpoint wander which radar glint may produce.

In addition to these types, semiactive systems are being investigated, with obvious analogy to laser designators and seekers. Similarly, millimeter-wave beam-rider missile guidance is being studied. For these examples higher power transmitters are needed, which generally rules out solid-state sources.

Airborne radiometric sensors are being extensively used by NASA for remote sensing[14,15] and by the Navy for navigation[15] and imaging.[16] For example, NASA's NIMBUS 6 satellite carried five superheterodyne radiometers with center frequencies between 22 and 60 GHz. Currently, NASA is operating a dual-frequency (90 and 183 GHz) airborne radiometer to measure atmospheric temperature data related to water content.[12,15]

Several types of millimeter-wave communications systems have been developed or designed. These include terrestrial point-to-point[17] or ship-to-ship systems whose carrier frequencies were chosen to take advantage of atmospheric propagation characteristics; enclosed, low-loss, TE_{01} mode, circular waveguide for use in wideband, long-haul, heavy-route communication systems; and satellite-to-satellite or satellite-to-ground links.

The most straightforward scheme that has been developed for terrestrial (surface) communications is a shortrange (5-20 miles) duplex unit operating at 38 GHz, which is a low atmospheric-attenuation region. The advantages of a millimeter-wave system over a microwave system include the availability of a narrow beam width (high gain) from a small aperture, broader bandwidths (possibility of frequency agility), and link privacy.

In other cases the choice has been to use a frequency near 60 GHz, where attenuation is high, so signal overshoot is low and covert operation is possible. Examples include a line-of-sight communicator for use between ships.[18] The design employs 3-inch diameter paraboloid reflectors (4.5 degree beamwidth), an IMPATT transmitter/local oscillator and battery-pack power. Transceiver weight is 2 pounds and battery pack 6 pounds. Other systems have been devised which emphasize low cost and civilian applications,[19] as well as advanced dielectric waveguide circuitry.[20]

For many years Bell Laboratories and other organizations developed components and technology in relation to the so-called circular-electric mode (TE_{01}) waveguide, which has been shown to provide extremely low loss (about 2 dB/km) over the frequency range from 33 to 125 GHz, while carrying about 220,000 voice circuits simultaneously. Complete systems have been developed in the U.S., Japan, and England.[21-24] Several years ago the Bell System installed a 14-km long field test system in New Jersey, and a similar 22.7-km length of experimental waveguide has been installed in Japan. Tests have apparently been highly successful.[24,25]

Early satellite communications in the 30-33 GHz region were carried out between the NASA Applications Technology Satellites (ATS-5 and ATS-6) and ground stations.[26] Satellite-to-satellite millimeter-wave relay links were also designed,[27] leading to the development of needed components at V-band, since most of these links would have taken advantage of the very large atmosphere attenuation near 60 GHz to provide isolation from ground receivers.

More recently a variety of satellite links has been reconsidered, partly for reasons of spectrum congestion and/or cost benefits.[28,29] It seems probable that further millimeter-wave applications will evolve in the near future.[30-32]

The examples above represent only a modest cross-section of millimeter-wave activities today. More could be said about extensive work in spectroscopy. radio astronomy, special uses of sensors (e.g., auto collision avoidance radar), and other fields. Certainly the growth in research and development has become much broader in recent years, and now there are overtones of possible millimeter-wave systems which may be produced in quantity,a long-awaited event and one which is much-needed if the area is to continue to grow.

References

1. N. B. Kramer, "Solid State Technology for Millimeter Waves," Microwave Journal, Vol. 21, pp. 57-61; August, 1978.

2. N. B. Kramer, "Millimeter-Wave Semiconductor Devices," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-24, pp. 685-693; November, 1976.

3. G. Kantorowicz, P. Palluel, and J. Pontvianne, "New Developments in Submillimeter-Wave BWOs," Microwave Journal, Vol. 22, pp. 57-59; Feb., 1979.

4. "Introduction to Extended Interaction Oscillators," Data Sheet No. 3445 5M, November, 1975, Varian Associates of Canada, Ltd., Georgetown, Ontario, Canada.

5. H. Jory, S. Heggi, J. Shively, R. Symons, "Gyrotron Developments," Microwave Journal, Vol. 21, pp. 30-32; August, 1978.

6. J. J. Gallagher, M. D. Blue, B. Bean, and S. Perkowitz, "Tabulation of Optically Pumped Far Infrared Laser Lines and Applications to Atmospheric Transmission," Infrared Physics, Vol. 17, pp. 43-55, 1977.

7. Special Issue on Microwave and Millimeter-Wave Integrated Circuits, IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-26, No. 10; October, 1978.

8. Special Issue on Millimeter Waves: Circuits, Components, and Systems, IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-24, No. 11; November, 1976.

9. Y. Chang, J. A. Paul, and Y. C. Ngan, "Millimeter Wave Integrated Circuit Modules for Communication Interconnect Systems," Final Report No. DELET-TR-76-1353-F on Hughes Aircraft Contract DAAB07-76-C-1353 with ERADCOM; October, 1978.

10. M. V. Schneider, "Low-Noise Millimeter Wave Schottky Mixers," Microwave Journal, Vol. 21, pp. 78-83; August, 1978.

11. R. N. Trebits, R. D. Hayes, and L. C. Bomar, "Millimeter Wave Reflectivity of Land and Sea," Microwave Journal, Vol. 21, pp. 49-53 and 83; August, 1978.

12. J. C. Wiltse, "Millimeter Waves - They're Alive and Healthy," Microwave Journal, Vol. 21, pp. 16-18; August, 1978.

13. N. C. Currie, J. A. Scheer, and W. A. Holm, "Mm-Wave Instrumentation Radar Systems," Microwave Journal, Vol. 21, pp. 35-42; August, 1978.

14. J. Hank Rainwater, "Radiometers: Electronic Eyes That 'See' Noise," Microwaves, Vol. 17, pp. 59-62; September, 1978.

15. J. M. Schuchardt and J. A. Stratigos, "Detected Noise Levels Guide Radiometer Design," Microwaves, Vol. 17, pp. 64-74; September 1978.

16. J. P. Hollinger, J. E. Kinney, and Ballard E. Troy, Jr., "A Versatile Millimeter-Wave Imaging System," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-24, pp. 786-793; November, 1976.

17. S. J. Dudzinsky, Jr., "Atmospheric Effects on Terrestrial mm-Wave Communications," Microwave Journal, Vol. 18, pp. 39, December, 1975.

18. R. T. Davis, "Mm Transceiver Provides Covert Communications," Microwaves, pp. 9, October, 1974.

19. Y. Matsuo, Y. Adaiwa, and I. Takase, "A Compact 60-GHz Transmitter-REceiver," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-24, pp. 794-797, November, 1976.

20. J. E. Kietzer, A. R. Kaurs, and B. J. Levin, "A V-Band Communication Transmitter and Receiver System Using Dielectric Waveguide Integrated Circuits," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-24, pp. 797-803, November, 1976.

21. R. W. White, M. B. Read, and A. J. Moore, "Recent British Work on Millimetric Waveguide System," IEEE Trans. Communication Soc. Vol. COM-22, pp. 1378-1390, September, 1974.

22. K. Miyauchi, S. Seki, N. Ishida, and K. Izumi, "W-40G Guided Millimeter-wave Transmission System," Review of Electrical Communications Laboratories, Vol. 23, pp. 707-741, July/August, 1975.

23. "Millimeter Waveguide Systems," Microwave Journal, Vol. 20, pp. 24-26, March, 1977.

24. "Japanese W-40 G Guided Millimeter-Wave Transmission System," Microwave System News, Vol. 6, pp. 91-97, February/March 1976.

25. W. D. Warters, "Millimeter Waveguide Scores High in Field Test," Bell Laboratories Record, pp. 401-408, November, 1975.

26. L. J. Ippolito, "Effects of Precipitation on 15.3 and 31.65 GHz Earth-Space Transmissions with the ATS-V Satellite," Proc. IEEE, Vol. 59, pp. 189-205, 1971.

27. J. W. Dees, G. P. Kefalas, and J. C. Wiltse, "Millimeter Wave Communications Experiments for Satellite Applications," Proc. IEEE International Conference on Communications, San Francisco, pp. 22-20 to 22-26, June, 1970.

28. N. B. Hilson, J. J. Gallagher, et al, "Millimeter Wave Satellite Concepts," Vol. I - Technical Report No. NASA CR-135227, NASA Lewis Research Center, Contract NAS3-20110, September, 1977.

29. N. E. Feldman and S. J. Dudzinsky, Jr., "A New Approach to Millimeter-Wave Communications," Rand Report R-1936-RC, April 1977.

30. L. G. Mundie, N. E. Feldman, "The Feasibility of Employing Frequencies between 20 and 300 GHz for Earth-Satellite Communications Links," Rand Report R-2275-DCA, May, 1978.

31. C.K.H. Tsao, W. J. Connor, and T. E. Joyner, "Millimeter-Wave Airborne Terminal for Satellite Communications," International Conference on Communications, 11th, pp. 36-4 to 36-8, 1975.

32. A. Castro, and J. Healy, "Transmitter System for MM Wave Satellite Communications," International Conference on Communications, 11th, pp. 36-9 to 36-13, 1975.