has a much better potential for frequencies above 100 GHz [4].

ACKNOWLEDGMENT

The author wishes to thank Dr. S. Weinreb, Assoc. Univ., Inc., for his encouragement and instrumentation support.

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The Challenge of Astronomy to Millimeter-Wave Technology

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Invited Paper

Abstract—**The inseparability of pure and applied science, or the synergy between scientific discovery and technological advance, has already been well illustrated in the field of radio astronomy. Recent astronomical discoveries in the millimeter range, and what can be expected to emerge from the far-infrared region, make further technological developments in these relatively unexploited areas of great interest to astronomy as well as technologically challenging. The nature of problems and the goals of astronomy in this area are discussed with particular reference to technological needs and developments.**

RADIO ASTRONOMY has benefited enormously from the steady advance of microwave technology; at the same time it has stimulated many of these advances. This important realm of astronomy originated in Jansky's engineering investigations of the early 1930's, grew rapidly with the help of wartime microwave technology, and recently has become all the more active following the discovery of complex molecules in interstellar clouds. So far, 38 species of molecules, some having as many as eight atoms, have been found in the large and relatively dense clouds of dust and gas within our galaxy, and a few species have been detected in external galaxies. The absorption or emission of molecular lines are associated primarily with their rotational motions; these resonance lines occur commonly in the centimeter region but are even more abundant and intense in the millimeter range. This adds great importance to the development of millimeter-wave technology. In addition, there are many molecular resonances at still shorter wavelengths in the submillimeter range. This latter region, which is presently almost completely unexploited, needs imaginative invention for its development as well as airborne or spaceborne platforms for any extensive astronomical use.

The relatively simple spectra of linear molecules are characterized by a series of almost harmonically related frequencies given to good accuracy by $\nu = (Jh/4\pi^2 I)$, where J is an integer, h is Planck's constant, and I is the molecular moment of inertia. For example, CO has lines at wavelengths 2.6 mm, 1.3 mm, and various other fractions of the fundamental wavelength 2.6 mm. Thus the lightest and simplest molecules have spectra only in the millimeter range or at still higher frequencies. More complex molecules, having three different moments of inertia and possibly internal rotational motions as well, have a more complicated spectrum which can give a variety of frequencies at both long and short microwave wavelengths. Generally, the shorter wavelength resonances, at least down to about 1 mm, are the more intense. In addition to rotational motions, there are some exceptional cases where molecular vibrations such as the inversion spectrum of ammonia, or even atomic hyperfine structure such as the 21-cm hydrogen line, fall in the microwave region. Molecules which have been found in interstellar clouds by their microwave spectra include many of the simplest, such as diatomic oxides and hydrides, but also a surprising number of organic molecules such as formaldehyde, dimethyl ether, various amines and acetylenes, and even ethyl alcohol.

Gas clouds containing molecules are interesting for a variety of reasons besides the existence of molecules there. They contain considerable solid materials in the form of dust

Manuscript received June 22, 1976. This work was supported by the Office of Naval Research under Contract N00014-69-A-0200-1003.
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grains, some of which are broadly similar to the silicates found in rocks on earth. They are also the typical spawning ground of stars, formed from the gravitational collapse of such clouds. This collapse in combination with stellar radiation tends to keep the clouds in turbulent motion and to produce very complex spatial distributions and Doppler velocities.

The excitement of molecular microwave astronomy has placed great demand on efficient and highly directional millimeter-wave antennas, as well as on very sensitive receivers for the millimeter range. There are, for example, very few sizeable antennas with adequate performance down into the realm of 1- or 2-mm wavelength. This shortage has led radio astronomers even to use optical telescopes at times with microwave heterodyne equipment for work at the shorter millimeter wavelengths. The largest and best millimeter-wave antennas still do not give the angular resolution which is desirable for some astronomical problems. Most molecular resonances detected are broadly distributed in clouds which may be a number of minutes of arc in angular size. However, quite a number of resonances are amplifying like a maser as a result of population inversion, and these are characterized by high radiation intensity from sources of very small angular size. There seems also to be good evidence, largely from presently available observation of molecular lines, that molecular clouds show a great deal of spatial structure smaller than the 1 min of arc, which is approximately the highest resolution afforded by present antenna beams. Study of these small regions calls for interferometers using two or more telescopes and aperture synthesis techniques, the techniques which have been used successfully for some time at longer microwave wavelengths.

The needs of astronomy by no means stop at the limits of the millimeter range. While most molecules have some resonant lines at wavelengths longer than 1 or 2 mm and hence can be studied to some extent by millimeter and centimeter techniques, there are many important molecular resonancies at shorter wavelengths; for example, in time the CO rotational spectrum is likely to be observed down to wavelengths of 1/10 mm or shorter. All or most of these wavelengths do not easily penetrate the earth's atmosphere, but in very dry air and at high altitudes radiation from extraterrestrial objects can be detected in the region near 0.3-mm wavelength. In airplanes or satellites, clearly important bases for astronomical work of the future, all the submillimeter region may be studied. This makes valuable and exciting development of sensitive and high spectral resolution techniques, such as linear amplifiers and heterodyne detection, down into the submillimeter region. The use of linear amplifiers and heterodyne detection is limited at very short wavelengths because of quantum or uncertainty-principle noise, which produces noise power of the form $P = h\nu\Delta\nu$, or an effective noise temperature of at least $h\nu/k$ where ν is the frequency and k is Boltzmann's constant. Hence microwave-like techniques involving linear detection become somewhat less appropriate at very much shorter wavelengths, but in special cases heterodyne detection and linear amplifiers are valuable down even into the middle infrared region with wavelengths as short as a few microns where $h\nu/k$ corresponds to noise temperatures of a few thousand degrees. For example, heterodyne techniques have recently been used with lasers as local oscillators in the 10-μm region for high spectral resolution of astronomical spectra, and for two-antenna interferometers. In the millimeter range, the quantum-produced minimum noise temperature corresponds to only about 10 K, considerably less than the noise usually produced by radiation from the imperfectly transmitting antenna or from the earth's atmosphere. Even down to about 1/10-mm wavelength, such quantum noise is not a serious limitation. Hence while linear detection techniques are not now in use for astronomy below a 1-mm wavelength, such techniques for the submillimeter range must surely be invented and developed in the long run because of their importance to astronomy and probably other fields which will emerge. For the more immediate future, further perfection of technology in the millimeter range can be expected to yield a wide variety of tremendously interesting results.

A critical parameter for a microwave telescope and detection system is its effective system noise. Noise is contributed by radiation from antenna losses, side lobes, and most importantly by radiation from the somewhat lossy atmosphere which varies in effective temperature from a few tens to a few hundreds of degrees, depending on the wavelength and moisture content of the atmosphere. The most variable and critical element of all in determining system noise is usually the quality of the receiver. While the noise temperature of a linear amplifier or detector must, as noted previously, be at least as high as $h\nu/k$, it is frequently very much larger, and in the millimeter range is usually a dominant source of noise. Radio astronomers observe for many hours in order to detect the weaker molecular spectral features with a signal-to-noise ratio just large enough to be certain that a signal exists, and under these circumstances the time required to detect successfully such signals is proportional to the square of the system noise temperature. Hence an observing period of a few weeks on an expensive antenna with a system noise temperature of 5000° can be reduced to about 10 min with a system noise temperature of 100°.

For detection and study of microwave continua, such as that emitted by regions containing ionized gas, a very broad-band amplifier is highly desirable; for the molecular work, narrow-band systems are usually quite adequate because the molecular lines have a limited fractional width. Their widths are determined by Doppler broadening, due to the turbulent velocities in interstellar clouds. Since these turbulent velocities are not generally greater than about 10 km/s, the fractional width of a molecular resonance is not much larger than this velocity divided by the velocity of light, or 3×10^{-5}, and a relatively narrow-band receiver can be appropriately used. From the preceding, it is clear that a millimeter-wave amplifier having a noise temperature somewhat less than that contributed by the atmosphere and antenna system ($\sim$100 K) and with a bandwidth as large as a few megahertz allows something close to optimum system performance obtainable from the earth's surface.

A further criterion is important to an amplifier and antenna system if it is to be used on an interferometer involving two or more antennas, i.e., for techniques generally known as long baseline interferometry, or aperture systhesis. Such systems have yielded remarkably high angular resolution on a variety of astronomical objects, for which baselines as long as intercontinental distances are sometimes used. To obtain accuracy in position rather than resolution alone, an interferometer must have its two antennas connected by a microwave line of fixed or determinable length, so that the relative phase of the partial wave received in the two or more antennas can be accurately known. Hence the additional property of antenna–receiver systems for radio astronomy, or of a sensitive amplifier used with such a system, is the stability of the phase relation between its input and output.

The large number of molecular resonances that have recently been detected and measured with some precision in the millimeter range have yielded much interesting astronomical information. But, as may be expected, the fruitfulness of this work uncovers further frontiers which demand still more extended and exacting measurements. For the moment, these demands for shorter wavelengths, more sensitivity, more directionality, and relatively precise measurements of power and frequency are probably greater than is immediately needed for most other purposes. However, their development can be expected to be rewarding both for astronomy and for other scientific experiments which become practical as new possibilities are made available. Perhaps somewhat later, but almost certainly somewhere in the future, we may also expect from them a variety of new technological and commercial applications.

K-Band Traveling-Wave Maser Using Ruby

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Abstract—**A *K*-band ruby traveling-wave maser (TWM) has been developed, which has provided a decrease in system noise temperature compared to other front ends presently used in radio telescopes at *K*-band by an order of magnitude. The maser uses a new type of photoetched slow-wave structure, integral with the ruby rod, especially suitable for millimeter-wave masers. It also employs a new type of built-in isolator configuration, which guarantees stable net gain of typically 30 dB over the tunable bandwidth, which is about 20 percent. Its phase stability, both short and long term, is excellent, making it highly suitable for use on an interferometer for radio astronomy.**

I. Introduction

MASERS have long been established as the lowest noise microwave amplifiers known, with present applications mainly in radio and radar astronomy as well as space communication receiver systems [1], [2]. Although laboratory masers have been operated up to 100 GHz, masers have not been in general use above 15 GHz, primarily because the limited applications of the higher frequencies did not warrant the development costs involved in adapting the laboratory maser versions for field use. Only the excellent Arams and Peyton maser, at 8 mm, was developed for this purpose [3], but was not intended for radio astronomy. More recently, a Russian ruby maser for use in radio astronomy at 8 mm has been described [4] as well as a Swedish design, which further developed the Arams–Peyton concept [5].

The discovery of a large number of interstellar molecules, most of which can be best detected at millimeter-wave frequencies, has given a new urgency to the development of low-noise millimeter-wave receivers for radio astronomy. The frequency range of the ruby maser reported here was chosen so as to incorporate the important inversion lines of ammonia (at $\geq$ 23.69 GHz) as well as the water vapor line at 22.235 GHz. The maser has also been used to observe or search for a large number of other molecules. The system noise temperature in a radio telescope using the maser is primarily determined by waveguide loss in the waveguide connecting the maser to the feed, and atmospheric thermal

Manuscript received October 30, 1975; revised June 28, 1976. The development of the *K*-band ruby maser was supported by the Office of Naval Research under Contract N00014-69-A-0200-1003.

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