SUBMILLIMETER WAVE SCIENCE AND APPLICATIONS

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Abstract - **Limitations imposed by the atmosphere at submillimeter frequencies have restricted researchers from retrieving crucial information regarding astronomical sources. With the availability of sensitive detectors and new generation of telescopes, the terahertz instrumentation has improved drastically over the past two decades. Recent technological developments in the THz region have lead to various applications in astronomy, atmospheric research, defense and medical fields. In this paper, we present the state-of-art high spectral resolution heterodyne receiver system from 300 GHz to 3 THz range with its possible future applications.**

1. INTRODUCTION

Submillimeter (SMM)/Far Infrared (FIR)/Terahertz (THz) region is the most promising region of the electromagnetic spectrum for observing key molecules in space [1-3]. To date about 130 kinds of molecules have been detected in the interstellar medium. These include many forms of water and organic molecules essential for sustaining life.

Due the fact that "approximately one-half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the submillimeter and far-infrared [4], THz technology developments is always closely watched by astronomers. Molecular lines are excellent probes of physical and chemical conditions in interstellar clouds, protostar envelopes, circumstellar shells around late-type stars, photon dominated regions etc. Furthermore molecular line transitions play a key role in probing the properties of galaxies and their evolution.

The development and demonstration of terahertz applications and technologies for operation in the range between 100 GHz to 10 THz (3 millimeter to 30 micrometer) has received increased interests and attention for different applications. The interests are to a large degree stimulated by such THz applications as space-based communications and atmospheric sensing. In addition, there are also tremendous interests in THz chemical and biological sensing. Furthermore, systems and methods for inspection in biomedical applications, healthcare and homeland security, which could detect and define covered damage & pathologic tissues, under skin vessels and organs, target identification of bio & chemical materials, be fast working and suitable in exploitation are urgently needed in medicine and in other fields. Research, in moving from simple detection to THz imaging, target identification and location of bio- and chemical materials, has recently gained tremendous momentum.

Exploring terahertz technologies for wider bandwidth communications and sensing for satellite systems, upper atmospheric imagery [5] etc. requires aggressive development and demonstration of THz sources and detectors. In this regard PRL is developing a high resolution heterodyne receiver system using optically pumped molecular laser as local oscillator and a Schottky diode [6] as a mixer. The SMM group is also indigenously developing front-line technologies for the ground based receiver system, which will be used in the ground based telescope observatory at Hanle. The conceptual design and optimization of the space born payload for the submillimeter observations are under way. Along with this, the group is developing important backend electronic devices such as Chirp Transform Spectrometer [7] indigenously.

2. HETERODYNE RECEIVER SYSTEM

The primary purpose of a heterodyne receiver system is to translate a signal at higher frequency (THz region) to the lower frequency (in the microwave region) where it can be amplified or processed more effectively. The SMM group of PRL is developing high resolution heterodyne receiver system using Schottky barrier diode as mixer and CO_2 pumped FIR Laser as Local Oscillator. In this receiver the incoming signal is mixed in a Schottky diode mixer with an FIR local oscillator (LO) beam with a frequency close to the signal frequency. Thus signal is down converted to the microwave range where low noise amplifiers and suitable filters exist. In the laboratory setup we are also doing the Submillimeter heterodyne spectroscopy of the molecules of atmospheric importance. In which the signal from the black-body is used to excite the gas molecules in the gas-cell at low temperature and pressure. In this way molecules move to higher vibrational excited states and then falls to original state through several rotational-vibrational transitions emitting submillimeter frequencies (ν_{SIG}). This signal is mixed with local oscillator signal at frequency ν_{LO} in a mixer. Thus we get the intermediate frequency ν_{IF}, $|\nu_{LO}-\nu_{SIG}|$, which is amplified and fed to spectrum analyzer. The spectral profile data so obtained are fitted into the various broadening profiles (e.g. Voigt and Doppler) after the noise filtration. Thus from general profile formulae all the necessary parameters regarding molecular system in the gas cell can be retrieved. The IF signal obtained from the first mixer needs amplification by chain of IF amplifiers to acquire suitable power level required for further signal processing. High Electron Mobility Transistor (HEMT) amplifier provides very high frequency operation with lowest noise figure.

The main parts of the receiver system are the mixer and local oscillator. We are indigenously developing the local oscillators and mixers in the THz region. Some of the components are described in the following section.

2.1 LOCAL OSCILLATOR SOURCES

2.1.1 Optically Pumped Molecular Laser: Presently Optically Pumped Molecular Lasers (OPMLs) are the only available sources for laboratory research. The entire THz/SMM region coverage is provided by OPMLs. In our laboratory setup, we are using this versatile OPML to generate required frequency of a particular molecular system. It consists of a grating-tuned carbon dioxide pump laser and a far-infrared cavity. The pump beam enters the cavity through an aperture in the highly reflecting resonator mirror cavity. The CO_2 laser is tuned to the appropriate absorption band to obtain lasing action in the FIR cavity. An active DC stabilization scheme is implemented to ensure stable FIR output. We are also pursuing research to fabricate an innovative wave guide laser cavity design for a compact and efficient LO system for the space mission.

2.1.2 Solid State Local Oscillator: Even though the OPMLs are proven workhorse for the high resolution laboratory spectroscopy, for the space mission they are too bulky and not practical. Solid state microwave sources (e.g. Gunn oscillator) and chain of frequency multipliers can be used as an alternative viable solution to the local oscillators. The selection of multipliers depends on the output frequency requirement. However being space qualified, compact and having tunability within the given frequency band, the output power is limited to few microwatts or less. This level of power is not sufficient to drive the Schottky mixer but is compatible with ultra sensitive superconducting mixers such as SIS and HEB.

2.2 IF SPECTROMETER

The spectral information of molecular transitions of an astronomical source can be retrieved by processing the IF signal from a mixer device through a spectrometer such as Acousto-Optic Spectrometer (AOS), Auto Correlator Spectrometer (ACS) and Chirp Transform Spectrometer (CTS). The requirement of bandwidth and frequency resolution for a particular source dictates the kind of spectrometer that can be used. Very large bandwidth and poor resolution can be obtained with AOS while ACS gives wide bandwidth and moderate resolution. The CTS is the choice of astronomers when very high resolution is warranted. Less weight, small size and low power are promising features of CTS which can be exploited for future space based missions. The Filter Bank spectrometer is very bulky and suitable only for ground based applications.

3.0 APPLICATIONS

A wide range of scientific investigations, from cosmology and the microwave background radiation, through astronomy, atmospheric and environmental science to laboratory spectroscopy and the properties of materials, have been carried out using latest submillimeter instrumentation. THz time domain spectroscopy and emission spectroscopy are widely used for the study of large bio-molecules, while THz imaging is being explored in fields as diverse as security and medicine. The SMM/THz field is undergoing a vigorous and exciting period of renaissance and the range of applications is wider than ever before [8]. At PRL, we are pursuing research to investigate various molecular clouds in the Inter Stellar Medium (ISM) and trace gas chemistry to under stand ozone cycle.

3.1 Astronomy/Astrophysics: Cold clouds of gas and dust in the Inter Stellar Medium (ISM) are the building block of the universe. These molecular clouds in our own galaxy, as well as in nearby galaxies, emit submillimeter radiation. Submillimeter wave observations of these clouds can detect protostars embedded in dense clouds of dust. The nucleus of M82 galaxy radiates as much energy in the terahertz/far-infrared as all of the stars in our Galaxy combined. This energy comes from dust heated by a source which is not visible in optical region. The central regions of most galaxies shine very brightly in the submillimeter/far-infrared. Several galaxies have active nuclei hidden in dense regions of dust. Others, called starburst galaxies, have an extremely high number of newly forming stars heating interstellar dust clouds. These galaxies, far outshine all others galaxies in the far-infrared.

Molecules play an important role for the physical state of the interstellar clouds. Low-energy rotational transitions of molecules such as CO, H_2O and possibly O_2 effectively cool the gas at low temperatures. Furthermore, the ionization fraction controls the coupling of gas and magnetic fields. Both of these parameters affect the ability of a cloud to collapse and therefore have profound significance for the process of star formation and ultimately the evolution of the Galaxy. Thus molecules can be used as spectroscopic probes of the physical conditions in interstellar clouds. Several submillimeter missions (e.g. Herschel, Plank) have been planned with the state-of-the art high resolution heterodyne receiver systems.

3.2 Atmoshperic Science: Ozone is a highly unstable molecule; it reacts very easily and is destroyed by reactions with chlorine, bromine, nitrogen, hydrogen, and oxygen gases. Reactions with these gases typically occur through catalytic processes. A catalytic reaction cycle is a set of chemical reactions which result in the destruction of many ozone molecules while the molecule that started the reaction is reformed to continue the process. Because of catalytic reactions, an individual chlorine atom can on average destroy nearly a thousand ozone molecules before it is converted into a form harmless to ozone. A number of catalytic cycles that influence stratospheric ozone at various altitudes have been studied by atmospheric chemists. The most effective cycles involve chlorine (Cl), bromine (Br), nitrogen oxides (NOx), and hydrogen oxide radicals (HOx). Natural catalytic cycles involving NOx and HOx have historically helped keep ozone levels in the atmosphere stable. All these intermediate molecules have signature in submillimeter region. High resolution spectroscopy provides abundance and other key information of the chemical reaction and in turn, ozone depletion.

4.0 PRESENT AND FUTURE PROSPECTS

During the next decade we expect tremendous advances in instrumentation for spectroscopy in submillimeter. In particular, large array detectors will bring revolution in bio medical imaging, air port security, and communication. A great deal is already known about the nature of the gas and dust in the interstellar medium, obtained from a wide variety of telescopes and facilities. The new receivers with greater bandwidth and sensitivity will provide opportunities in the area of Astrochemistry of distant objects, through new spectral range.

With the existing facility, we are studying the spectral features (line position, line strength and line width) of various atmospherically important gases like H_2S and N_2O in different environmental conditions such as pressure and temperature. In very near future, we are extending our interest towards astronomically and astrophysically important molecules, ozone depletion analysis, and THz imaging.

5.0 CONCLUSION

The laboratory receiver system is ready and is being used for the laboratory spectroscopy of the planetary and atmospherically important molecular systems. We are also developing compact space qualified receiver system in parallel. We are planning to exploit the national telescope facility at Hanle and the balloon facility at Hydrabad for studying selected astronomically important molecular lines. All our effort consists of developing space-qualified receivers in the submillimeter wave range.

REFERENCES

[1] H.P. Röser, “Heterodyne spectroscopy for submillimeter and far-infrared wavelength from 100 µm to 500µm,” *Infrared Physics*, Vol.32, pp.385-407, 1991.

[2] D.T. Jaffe, A.E. Harris and R. Genzel, “Warm dense gas in luminous protosteller regions: A submillimeter and far-infrared CO line study,” *Astrophys.J.*, Vol.316, pp.231-242, 1987.

[3] A. I. Harris et.al. “First observations of the CO J=6-5 transitions in starburst galaxies,” *Ap. J. Lett.,* 1991.

[4] Siegel, P. H., “Terahertz Technology,” *IEEE Trans. on MTT***,** Vol. 50, pp. 910, 2002.

[5] J. W. Waters, “Microwave limb sounding of the earth’s atmosphere,” *Atmospheric research*, Vol.23, pp.391- 410, 1989[6]. Thomas W. Crowe, “GaAs Schottky diode for THz mixing applications,” *Proceedings of IEEE*, Vol.80, No.11, 1992.

[7] Darligton S.,”Demonstration of wide band low power FM signals,” *Bell Syst. Tech. J.* 43, pp. 339, 1964.

[8] Proc. Joint 29th Int. Conf. on Infrared and Mm. Waves and 12th Int. Conf on THz Electronics, IRMMW 2004/THz 2004, Sept. 27 - Oct. 1, 2004, Karlsruhe, Germany, Eds. M. Thumm and W. Wiesbeck, IEEE Catalog No: 04EX857, ISBN: 0-7803-8490-3, Library of Congress: 2004104546.