Bulk and Integrated Acousto-Optic Spectrometers for Radio Astronomy

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One of the most significant developments in radio astronomy has been the recent discovery of over 50 different molecules in the interstellar medium. These observations have changed our picture of the distribution of mass in the galaxy, altered our understanding of the process of star formation, and also opened up a new and lively field of interstellar chemistry. This achievement was made possible not only by the development of sensitive heterodyne receivers (front-end) in the centimeter and millimeter range, but also by the construction of sensitive RF spectrometers (back-end) which enabled the spectral lines of molecules to be detected and identified. Traditionally, spectrometers have been constructed as banks of discrete adjacently tuned RF filters or as digital auto-correlators. However, a new technique combining acoustic bending of a collimated coherent light beam by a Bragg cell followed by detection by a sensitive array of photodetectors (thus forming an RF acousto-optic spectrometer (AOS)) promises to have distinct advantages over older spectrometer technology. An AOS has wide bandwidth, large number of channels, and high resolution, and is compact, lightweight, and energy efficient. These factors become very important as heterodyne receivers are developed for ever higher frequencies.

The thrust of receiver development is towards high frequency heterodyne systems, particularly in the millimeter, submillimeter, far infrared, and 10 μm spectral ranges. The motivation for this development comes from the need to determine the chemical composition of the interstellar medium and to achieve a thorough understanding of the excitation of interstellar molecules. The most important constituent of the interstellar medium after molecular hydrogen is carbon monoxide (CO) which has its rotational transitions at 115.3, 230.5, 345.8, and 691 GHz, etc., while hydroxyl (OH), an equally important constituent, has its ground-state rotational transition at 2508 GHz. In general, the lighter the molecule, the higher its ground-state transitions which fall often above currently accessible receiver ranges.

The LO, LO coupler, and mixer present difficult challenges as the range of the receiver is extended towards higher frequencies. Klystrons which are already expensive and short-lived in the 3 millimeter range become impractical at shorter wavelengths forcing development of frequency doubling or tripling mixers utilizing cheaper and more robust lower frequency LOs. In the 10 mm band the CO_2 gas laser-heterodyne system, with its various isotopic mixtures, can cover only about 10% of the spectral band due to the limited tunability of the gas laser transition and limited bandwidth response of mixers. Work is presently underway in this laboratory to construct a diode heterodyne system which will have a 2 mm continuously tunable range. RF tuned cavity LO couplers which work well in the 3 millimeter wavelength become highly lossy in the millimeter range forcing development of quasi-optical techniques to combine signal and LO efficiently to the mixer. Mixer development is also continuing to extend usable range of mixers into the far infrared and 10 mm bands. Recently we have used a 25 watt CO_2 10 mm laser to pump a formic acid 430 mm laser in an experiment on the 3-meter IRTF in Mauna Kea to detect and map the 691 GHz, $J = 6 \rightarrow 5$ transition of CO in Orion and other galactic sources.

Common to all heterodyne systems is an RF spectrometer (back end) which recovers the power spectrum of the signal from the IF. Traditionally the spectrometer is a bank of discrete adjacently tuned RF filters or a digital auto-correlator. Most radio telescopes have 256 or 512 channels at 1 MHz or 0.25 MHz resolution. Heterodyne receivers in the millimeter, submillimeter, or far infrared will be operated from remote mountain, airborne, balloon-borne, or spaceborne platforms to avoid the severe atmospheric attenuation in the 20 mm to 1 mm range. This will place severe demands of size, weight, and energy usage on the back end which RF filters may not be able to satisfy.

Recent developments in acousto-optic techniques and in photodetector arrays have made feasible a new type of RF spectrometer offering the advantages of wide bandwidth, high resolution, large number of channels in compact, lightweight, energy efficient, and relatively low cost systems. Such a system employs an acousto-optic diffraction cell which serves the key role of converting RF signals to ultrasonic traveling waves modulating the optical index of the cell. The cell is illuminated across its aperture by a monochromatic laser beam. A fraction of the light is diffracted by the acoustic waves; the angle of diffraction is determined by the frequency while the intensity of the diffracted light is proportional to the power of the input RF signal. (The major portion of the laser beam at zero order passes through the cell undeflected.) A focusing lens follows the cell and essentially performs a Fourier transform of the RF signal into a far-field intensity pattern. The output intensity distribution is typically received by a linear array of photodetectors whose output is the RF power spectrum we seek. The advantage of an AOS is due to the simplicity arising from the small number of components needed to build up the system.

Currently there is intense commercial interest in applying acousto-optic techniques to electronic warfare (EW), electronic counter measures (ECM) and electronic support systems (ESM) which is spurring rapid technical advancements in the field. The Air Force and Navy, in a joint effort, are funding research at GTE-Sylvania, ATI-Itek, ESL, Teledyne-MEC, and Rockwell International in bulk Bragg cell AOS components. One benefit from this research is the commercial availability of 1 GHz bandwidth, 1 MHz resolution Bragg cells. The Air Force and the Navy have also funded Hughes Research and Westinghouse in an effort to further miniaturize an acousto-optic system by integrating all its components on a single substrate. These recent developments have made acousto-optic techniques increasingly attractive for use in astronomical applications.

We are currently both experimenting with a bulk and awaiting delivery of an integrated AOS device for astronomical research here at Goddard. The GSFC prototype AOS uses a discrete bulk acoustic wave Itek/Applied Technology Bragg cell with 300 MHz bandwidth (specified) 0.67 MHz resolution (500 resolution elements), 5 mW Spectraphysics Model 120 helium-neon laser with aluminum optical bench components assembled from Klinger Scientific. The length of the stainless-steel rods is 1 meter, and although the optical layout is fairly compact, no attempt was made to optimize the unit for size. The laser is located on the bottom of a two tier construction, with the beam directed to the upper level by guiding mirrors. A beam expander (16X) is placed in front of the Itek Bragg cell with the cell mounted on X-Z position translators. An aberration-minimized biconvex lens 80 mm in diameter with a 47 cm focal length follows the Bragg cell. The diffracted light is then guided downward by a mirror flat, and the output light is detected by a 1024 element CCPD Reticon array mounted on precision rotation and translation stages. The interlocking construction of the Klinger assembly gives the system very good rigidity and once the optical path has been aligned, retains its alignment even after movement of the assembly as a unit. Although no attempt has been made to temperature control the assembly the AOS appears to drift less than 1 channel over a 24-hour period.

The Itek/Applied Technology Bragg cell is made from a 1 cm optical aperture $LiNbO_3$ crystal with a specified 300 MHz bandwidth centered at 450 MHz. The interaction time is 1.5 ms with a time-bandwidth factor of 450. The diffraction efficiency of the cell is reported to be 7%/watt of RF power. Preliminary results of the GSFC AOS are given elsewhere[1].

An exciting prospect is the use of integrated optics in further miniaturizing an acousto-optic spectrometer. Recently, Westinghouse, under NRL contract and GSFC participation, has constructed a 400 MHz bandwidth, 140 element integrated AOS[2]. This entire RF spectrometer has dimensions of 7X3 cm. The spectrum analyzer, shown schematically Fig. 1, consists of a laser, a diffraction-limited geodesic collimating lens, a surface acoustic wave (SAW) transducer array, a second diffraction-limited geodesic lens that is utilized as a transform lens, and a 140 element photodiode array. A Te polarized 100-mW He-Ne laser operating at 0.6328 mm was end-fire coupled into the spectrum analyzer for preliminary testing. Efforts are now underway by Westinghouse to butt couple a diode laser source to the substrate.

The spectrum analyzer was fabricated on X-cut $LiNbO_3$ with the c axis parallel to the acoustic propagation. The optical waveguide was formed by diffusing 180 A of titanium into $LiNbO_3$ to obtain a tightly confined optical beam. The photosensor array was butt coupled at a 45° angle to the waveguide edge of the $LiNbO_3$ substrate in an optically polished Cer-Vit mounting block. This angular mounting minimizes spurious signals due to reflected light from the surface of the photodiode array and waveguide substrate.

The laser beam is coupled into the waveguide and collimated by the first geodesic lens. The SAW spatially modulates the guided optical beam. The deflected beam is focused onto the output edge of the optical waveguide. The butt-coupled photodiode array then detects the deflected beam. The deflection angle is proportional to the frequency of the RF signal. Therefore, the frequency of an incoming signal can be determined from the position of the focused beam on the detector array.

The geodesic lenses are circularly symmetric aspherical depressions in the surface of the waveguide and are fabricated by single-point diamond turning. The advantages of using single-point diamond turning for fabricating geodesic lenses are numerous. First, the lens can be precisely located on the substrate, which allows the focal plane of the lens to be placed at a predetermined position. Second, the lens profile can be cut to tolerances of better than 0.5 mm, which gives diffraction-limited performance and predetermined focal lengths. Finally, surfaces of the lenses can be cut very smoothly, thus eliminating the need for much post-machining surface polishing. We have measured the performance of diamond machined lenses and have found them to be diffraction-limited with an insertion loss of 2 dB, and to have a focal plane which is within 12 mm of the previously polished waveguide edge.

The detector array is a self-scanned photodiode array consisting of 150 photodiode pixels with a 12-mm pitch. The maximum shift register clockrate is 5 MHz, resulting in an access time of 2 msec. The maximum measured output voltage was 1.0 volt while the minimum measured output voltage was 90 mvolt, which yields a dynamic range of 40 dB. The next nearest neighbor crosstalk was down by 15 dB. A single zeroth-order beam sensing photodiode is included on the 6.4-mm square chip. The array is divided into 7 pixel groups of 20 pixels each. Each group is addressed in parallel by a 10-stage dynamic PMOS shift register. Each group has two electrometer output circuit channels; one handles odd pixels, while the other handles the even pixels for each clock cycle of the PMOS shift register. This scheme provides fourteen parallel samples every clock cycle.

The surface acoustic wave transducers are a two-element tilted array designed to have a combined 400-MHz bandwidth centered at 600 MHz. The operation of the spectrum analyzer and the frequency range over which the transducers operate are shown in Fig. 2. A separate measurement of the transducer performance provided 3-dB bandwidth of 400 MHz and a 5% deflection efficiency with an RF power of 60 mW.

In summary, this laboratory is in the process of constructing and evaluating bulk AOS devices with 300 MHz and 1 GHz bandwidths for use in the back end of high frequency heterodyne receivers for use in astronomical research. In addition, we are in the process of obtaining and will evaluate the feasibility of using integrated AOS devices as potential back ends for future balloon-borne or space experiments using heterodyne receivers.

References

1. SPIE Proceedings 1980 International Optical Computing Conference, Volume 231, p. 30, Chin, Buhl and Florez.

2. Applied Optics, Volume 19, No. 18, September 15, 1980, Mergerian, Malarley, Pautienus, Bradley, Marx, Hutchenson, and Kellner.

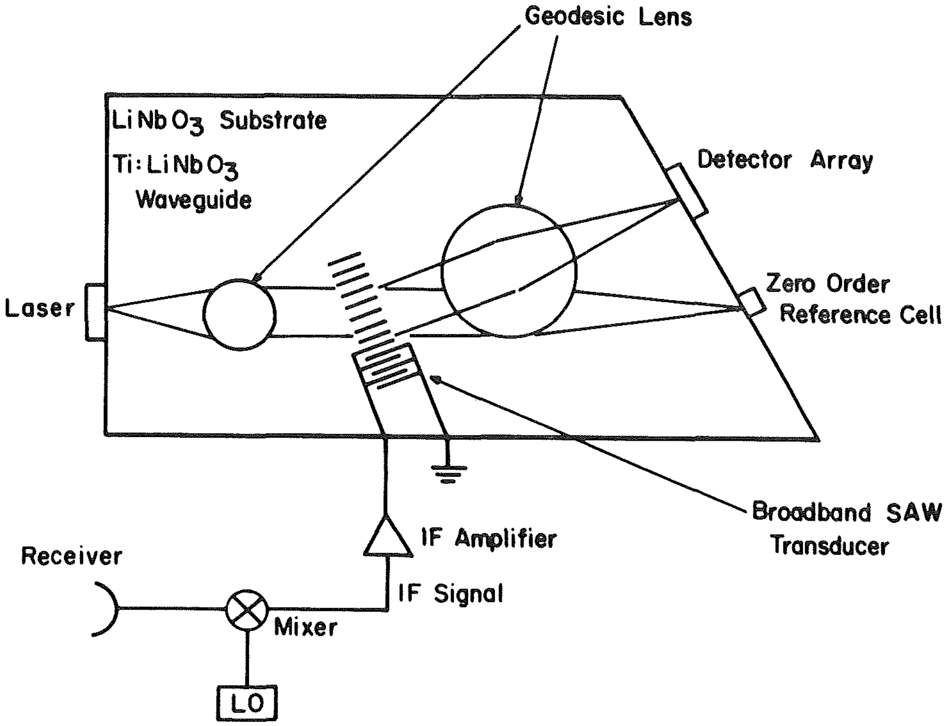

Figure 1.- Schematic of an integrated acousto-optics spectrometer.

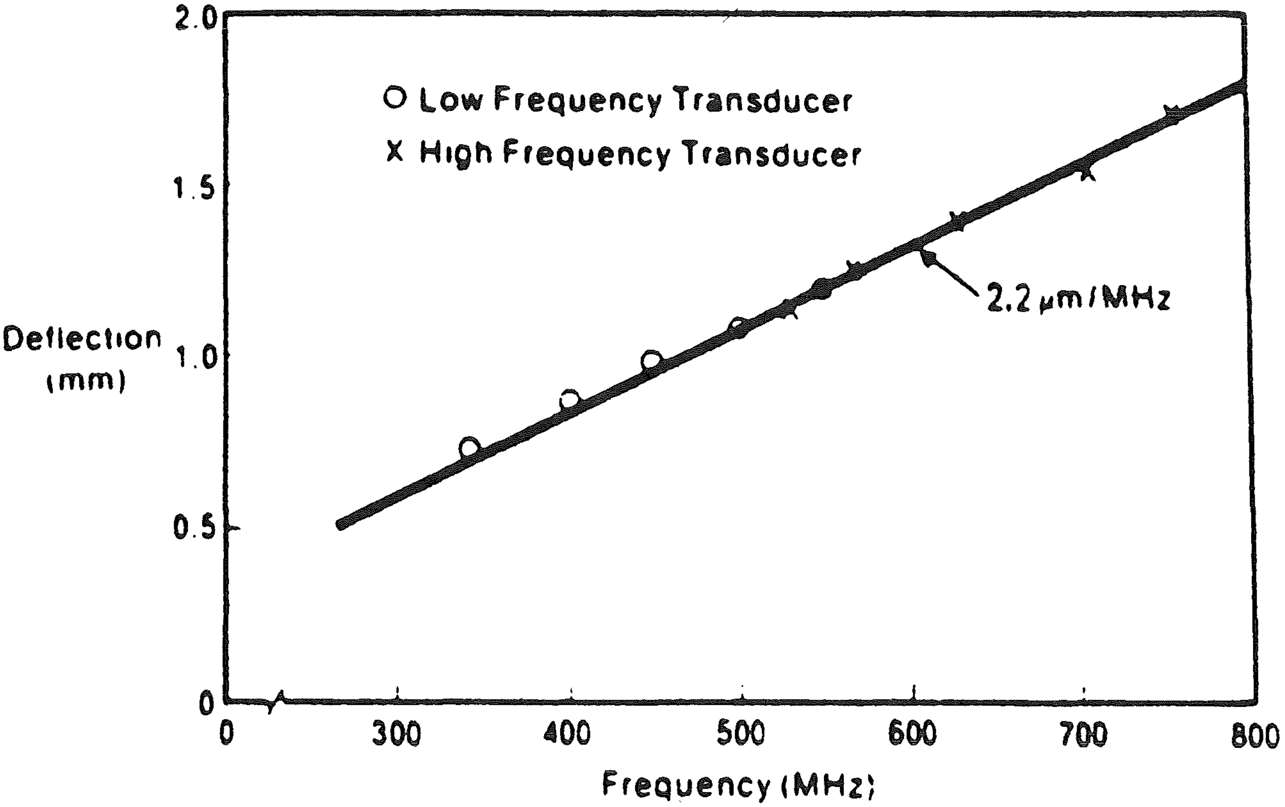

Figure 2.- Deflection of optical guided wave as a function of surface acoustic wave frequency.