RF SPECTRUM ANALYSIS USING OPTICAL WAVEGUIDES

Invited Paper

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ABSTRACT

Military radar environments require wideband, high resolution, high probability of intercept RF receivers for signal sorting. An Integrated Optical RF Spectrum Analyzer utilizing the Bragg diffraction of guided optical waves by surface acoustic waves has great potential for furnishing that capability. Besides having projected performance competitive with other technologies, Integrated Optics offers reduced size and cost. The state-of-the-art of optical waveguide componentry has now progressed sufficiently to make possible the development of a feasibility model of such a circuit.

Introduction

RF receivers that are capable of detecting and identifying radar threats are required in order to ensure survivability and effectiveness of military platforms in adverse environments. In order to avoid detection and classification, radar transmitters counter with techniques such as frequency hopping, pulse jittering, and spectrum spreading. Thus, an ever increasing spatial density and complexity of military radar systems continually erodes the utility of conventional RF receivers such as crystal video, scanning superheterodyne, and IFM. Electronic support measures (ESM) and electronic intelligence (ELINT) receivers intended for use in the 1980's must therefore possess high probability of intercept characteristics in order to cope with anticipated complex signal environments. Additionally, the receivers will be required to possess sensitivity and accuracy comparable to a narrow band superheterodyne receiver, to possess a cost comparable to present day FM receivers, and to be configured to provide a signal direction of arrival DOA information in addition to spectral analysis. With these capabilities, signals may be sorted by spectral emission characteristics, DOA and by pulse repetition interval (PRI).

A generalized RF receiver system presently under study is illustrated in Fig. 1. The RF "front end" conditions the collected signals and divides them into bands of interest (A,B,C, etc.) which are then processed by one or more "channelizers." Each channelizer separates the incoming signals in its band according to frequency. The preprocessor performs the necessary electronic operations to compose the signature of the received signals. Desirable measurement capabilities for the channelizer-preprocessor are in the ranges of 1-10 MHz for frequency resolution, 0.5-5.0 μsec accuracy for time of arrival and 40 dB or more dynamic range. The threat analyzer then interprets the signatures to formulate an output upon which the vehicle's response is predicated. While all elements of this generalized receiver present technological challenges, our focus in this paper is on the acoustooptical Bragg channelizer.

A schematic of an integrated optical spectrum analyzer is shown in Fig. 2. Incoming radar signals are mixed with a local oscillator and an IF is generated. This IF is tailored to fall within the acousto-optic bandpass. The IF is applied to an interdigital transducer array and generates a surface acoustic wave. An optical beam interacts with the surface acoustic wave, through the Bragg effect, and is deflected. The deflection angle is proportional to the frequency of the acoustic wave. Therefore, by sensing the position of the deflected optical beam, the frequency of the acoustic beam can be uniquely determined. An output waveguide lens focuses the diffracted light onto a linear detector array. The intensity distribution of the light at the detector array can be shown to represent the power spectral density of the input RF signal. The application in electronic warfare of Bragg deflection technology for spectrum analysis is particularily attractive because conventional CW or pulsed waveforms can be analyzed, the response can be wide open and extremely fast, and consistent, fine grain resolution can be realized.

The light path in the IO circuit from laser to detector array is entirely in optical waveguides which may be thin dielectric films or diffused layers at the surface of a suitable substrate. This planarity of construction leads to expectations of small size due to compactness in the dimension transverse to the waveguide plane and low cost through batch fabrication techniques. The waveguides are regions of increased refractive index (relative to the substrate and superstrate) of dimension comparable to an optical wavelength (λ = 1 μm). The SAW beam propagates with most of its energy within one acoustic wavelength of the surface ($\Lambda \simeq 5$ μm). This compaction of the optical and acoustic beams leads to a diffraction efficiency that is inherently greater than in a bulk device.

The dimension constraints on the size of the IO circuit in the waveguide plane are similar to those for a bulk acousto-optic spectrum analyzer. The e^{-2} width, D, of a truncated Gaussian optical beam required to achieve an RF frequency resolution, ΔF, is given by

$$D = \frac{1.41\ QV}{\Delta F} \tag{1}$$

where V is the SAW velocity and Q is the ratio of the actual focused spot size to the diffraction limited spot size. The output lens focal length required for frequency resolution ΔF is given by

$$f = \frac{VS}{\lambda_g \Delta F} \tag{2}$$

where S is the detector array periodicity and λ_g is the light wavelength in the waveguide. These equations are plotted in Figs. 3 and 4 for typical values of the parameters. As can be seen, the Bragg cell pulse response (Eq. 1) is determined by the optical aperture illumination profile which is probed as the pulse traverses the Bragg cell. Therefore, there is a trade-off between the temporal signal response and the resolution in Bragg receivers. A figure of merit by which to measure Bragg cell performance is its time-bandwidth (T.BW) product. The T.BW product determines the number of resolvable frequency components. Bragg cell dynamic range, on the other hand, is determined by optical scatter present in the circuit. This optical background limits the sensitivity on the low end whereas acoustooptical nonlinearities represent the large signal limitations. For moderate to low powers, however, the Bragg effect is very linear permitting the detection of multiple simultaneous signals without cross-modulation products (cross products being more than > 60 dB down).

Significant advances have taken place in the last year that now make it possible to fabricate a functioning IO spectrum analyzer. The following table summarizes the status of the relevant laser, IO, and detector technology.

TABLE 1. Integrated Optics Technology Status

Light Generation and Coupling: Semiconductor lasers now operate CW at 300°K with 10 mw output with $\Delta\lambda \approx$ 0.1 nm.[1] Butt-coupling efficiency to optical waveguides is over 40%.[2]

Waveguides: Overall attenuation less than 1 dB/cm for $Ti:LiNbO_3$ waveguides and thin film waveguides on oxidized silicon.

Waveguide Lenses: Sputtered lens on oxidized silicon diffraction limited at F/4 for 40% of the aperture.[3] Geodesic lens in $LiNbO_3$ at F/1.7 corrected for aberrations over 90% of the aperture.[4]

Waveguide Bragg Cell: 500 MHz acousto-optic bandwidth with $LiNbO_3$ substrate using multiple, tilted, frequency staggered transducers.[5]

Detector Arrays: Waveguide photodiode array with CCD readout demonstrated.[6]

The table shows substantial progress in all facets of the technology, though more improvement is needed in many of the areas before the ultimate performance can be obtained from an IO spectrum analyzer. The present state-of-the-art would probably yield a device with about 500-800 MHz bandwidth, 4-10 MHz resolution and 30-40 dB dynamic range. Eventually, it seems reasonable to expect 800-1000 MHz bandwidth, 1 MHz resolution, and 40-50 dB dynamic range. To achieve this potential requires reduction of lens aberrations and waveguide scattering, improvement in Bragg cell efficiency, and an increase in detector array dynamic range.

Summary

This paper will detail the state-of-the-art of integrated acoustooptical spectrum analyzers which are intended to be used in radar warning receivers. Advantages in performance, cost and size will be illustrated and an assessment will be presented as to the state of optical component integration that can be achieved and the expected performance.

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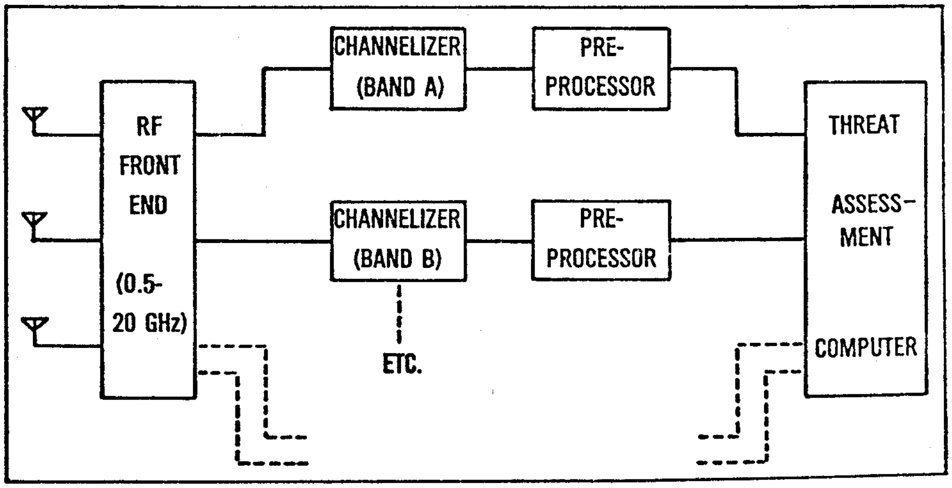


FIGURE 1 - Generalized RF Receiver Configuration

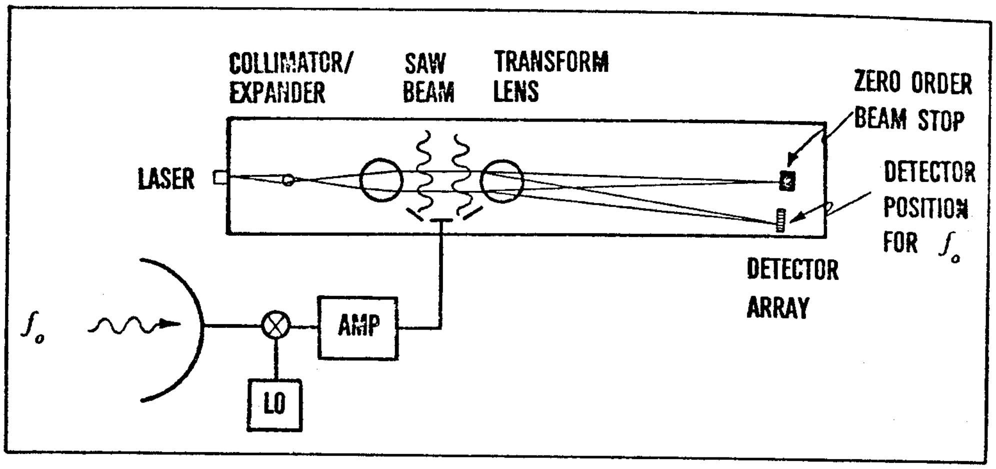
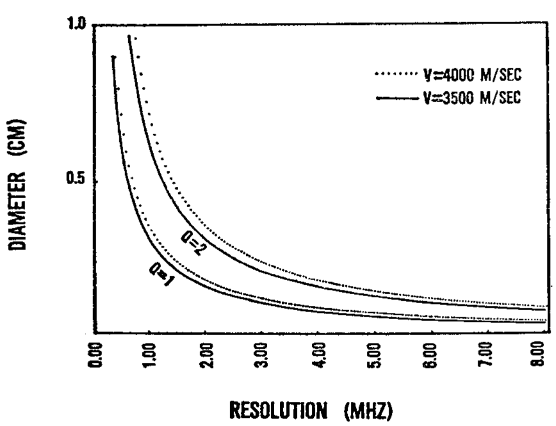
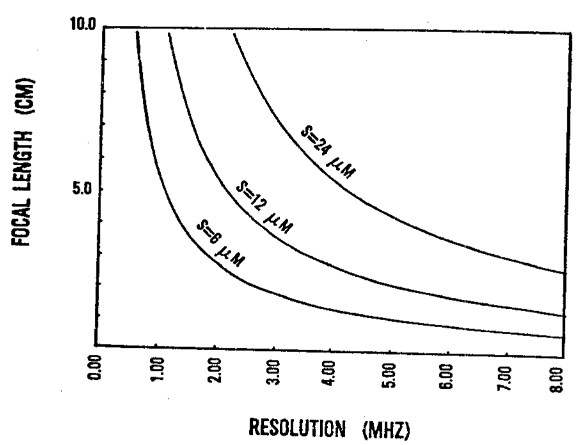


FIGURE 2 - Schematic for Integrated Optical RF Spectrum Analyzer





3 - Optical Diameter D required to achieve a frequency resolution ΔF. Solid line for a $LiNbO_3$ and dotted line is for a silicon substrate. The parameter Q describes the system optical quality.

FIGURE 4 - Transform lens focal length T required to achieve a frequency resolution ΔF. Curves are approximately valid for either silicon or $LiNbO_3$. The parameter S is the detector array periodicity.