Bignell

PERFORMANCE CONSIDERATIONS FOR CORRELATING ACOUSTO-OPTIC SPECTROMETERS.

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MILLIMETER ARRAY MEMO NO. 7

INTRODUCTORY COMMENTS:

The principle of operation of the acousto-optic spectrometer is well known. Figure 1 illustrates the basic concept. The signal to be analysed is coupled to an acoustic wave propagating in a dielectric material, which diffracts and modulates a laser beam passing through the transducer medium. The first diffraction order of the modulated beam is imaged onto an electro-optic sensor array, comprising an array of CCD or photodiode devices. The angular deviation of the diffracted beam is proportional to the signal frequency, whereas the laser light at a given angle carries the intensity and phase modulation impressed on it by the RF input signal at the corresponding frequency. The output of the sensor array is usually regularly scanned and digitized for further processing in a digital computer. A number of different workers have successfully constructed operational single input spectrometers, using commercially available components, exhibiting high sensitivity, good stability and bandwidths of 100-300 MHz with 1000 channel spectral resolution. Acousto-optic deflectors are now available with bandwidths of up to 1500 MHz and deflection efficiencies of 1.8%/watt of input power, using LiNbO(3) technology.

For use with a linear antenna array or interferometer, the spectrometer should also enable the determination of the cross correlation between two or more input signals. An acousto-optic realization of a cross correlating spectrometer is illustrated in Figure 2. In this case, the coherent laser beam is divided between N identical acousto-optic modulators, each fed with an IF signal from a unique element of the antenna array. The spacing and geometry of the transducer array mimics the configuration of the array. The separately modulated laser beams interfere when imaged onto a two dimen--sional image plane or sensor array, generating a one dimensional fringe pattern at a given angular deviation corresponding to a given input frequency component (see Figure 2). The brightness distribution of the sources in the field of view of the antennas can, in theory, be reconstructed by measuring, for many different antenna baselines, the amplitude and phase of the optical fringes at each angular deviation (or IF input frequency).

BASIC GEOMETRICAL CONSTRAINTS:

a) In order to separate $N(N-1)/2$ possible cross correlations, the following constraints must be met (for notation refer to Figure 2)

$$\begin{aligned} &w > N*(N-1)*w0/2 \\ &w0 \gg w' \qquad\qquad (1) \\ &w'' > 10*N*(N-1)*dw'' \end{aligned}$$

Furthermore, to reduce fringe smearing to below 5%, dw'' must be less than $(lam/w)/6$, or 1/6 of a fringe wavelength (lam is the light wavelength).

b) The deflection angle (dq) of the deflected light as a function of frequency is given by

$$dq/df = lam/vs \qquad (2)$$

where vs is the speed of sound in the acoustic material.

c) The frequency resolution, limited by the diffraction spot size, is given by

$$\#f = (lam/d)/(dq/df) \tag{3}$$

where d is the modulator aperture length.

d) The focal length of the lens required to match the detector element size, dw", to the frequency resolved light spot is

$$F = dw''*d/lam \tag{4}$$

PHOTODETECTOR NOISE CONSIDERATIONS:

The signal to noise ratio, S, at the output of the photo-diode array must satisfy

$$S > a*(B*t/Nd)^{1/2} \tag{5}$$

where a is a factor relating the allowable signal to noise ratio of the detector/integrator to the allowable overall degradation in system S/N, t is the integration time, B is the total IF bandwidth and Nd is the number of frequency resolving elements in the photo-diode array (PDA). In practice, the available S/N is limited by a combination of photon shot noise and readout speed for the PDA.

The ultimate limit on S for photo-detectors is photon shot noise. If each element of the PDA collects Np photons, then its S/N is given by

$$S = Np^{1/2} \tag{6}$$

The total number of photons collected by a column of the array in one integration period is Nd*Np and the rate of collecting photons is

$$R = Nd*Np/t > B*(a^2) \tag{7}$$

for a shot noise limited detector.
For an N input, correlating spectrometer

$$R > (N^2)*(a^2)*B \tag{8}$$

For a fast general purpose computer, the maximum practical readout speed constrains (t/Nd) > 10usec. If a special purpose integrating buffer memory were used (t/Nd) > 2 usec might be obtainable. The readout speed is related to the obtainable PDA signal to noise ratio by

$$S^2 = (N^2)*(t/Nd)*(a^2)*B \tag{9}$$

There exists two types of photodetector devices; CCD and photodiode arrays. CCD devices are essentially shot noise limited and have typical saturation levels of 2x10^5 to 10^6 photoelectrons. Photodiodes have saturation levels of 2x10^7 and S/N ratios of about 10^3 at room temperature. Cooling these latter devices should enable shot noise limited performance to be approached.

POWER REQUIREMENTS:

The laser power required to properly illuminate the photodiodes in the array is given by

$$Pl = (N^3)*Nd*(d/w0)*(1/n)*Pd \qquad (10)$$

where n is the diffraction efficiency of the deflector and Pd is the saturation power level of the photodetector. This equation assumes that the photodiode spacing is matched to the diffraction spot width and that there are no light losses in the system from spillover, reflections, etc. Typical optical efficiencies obtained in practice have been of the order of 5%, so the actual laser power requirement is about 20*Pl.

ARRAY DETECTORS:

The light utilization of the sytem can be improved by using an integrated 2-D array of photodetectors. The only arrays available of suitable size are CCD devices with saturation levels of about 10^6 photoelectrons. These devices operate in the shot noise limited mode at room temperature. If the detector array shape is not well matched to the diffraction pattern of the deflector, which is typically the case for commercially available arrays, then readout time spent handling data from the poorly used detectors in under illuminated areas of the array is wasted and the signal to noise ratio achieved will will be degraded.

Commercially available 2-D detector arrays presently have a maximum length of about 500 elements. The number of spectral channels would therefore be limited to less than 500 unless more than one device is used.

TYPICAL NUMERICAL EXAMPLE:

Typical LiNbO(3) deflector has the following properties:
B = 500 MHz
w0 = 0.3 mm
d = 25 mm
vs = 6.57x10^6 mm/sec
n = 5%/watt
lam = 6.328x10^4 mm
giving the following
dq/df = 9.6x10^-5 rad/MHz
#f = 657 KHz
F = 0.47 m
For N = 2 and less than 5% degradation in system S/N out to the -3 dB points of the IF band R > 2.83x10^10 photons per second.
If (t/Nd) = 10 usec, then the minimum number of photoelectrons per detector is 2.83x10^5, or a capacity of 4.66x10^5 for a detector operated at half saturation level. This is marginal for most CCD detectors but well within the capabilities of a photodetector diode linear array.
A 2x10^7 photoelectron saturation level photodetector in a cooled system could work with a data handling time of greater than 100 usec.
However, the required saturation level increases in proportion to the square of the number of deflectors or antennas in the intererometer. If N = 10, R > 1.07x10^11 photons/sec and, at (t/Nd) = 10 usec, the photodetector saturation level is required to be 1.4x10^7, marginal even for a photodetector array.

The required laser power for a two element interferometer system is given by Pl = 2 mW * (System optical efficiency) for an uncooled 1024 photodetector array, B = 500 MHz, and (t/Nd) = 6 usec. If the optical efficiency of the system is 5%, then the required laser power is about 40 mW. Cooling the detector could reduce this requirement by as much as a factor of 20 to about 2mW. The required power increases as the cube of the number of interferometer elements - if N = 10 , the required power increases to about 250 mW. The optical efficiencies assumed here are probably optimistic, and will certainly degrade with increasing system complexity.

CONCLUSIONS REGARDING APPLICABILITY TO MM-WAVE ARRAY:

From the foregoing discussion it can be seen that the construction of an operational two input correlating acousto-optic spectrometer using currently commercially available components is certainly practical. A spectrometer which degrades the total system S/N by less than 5%, with 1024 frequency channels and 1000 MHz total bandwidth would be possible using a cooled photodiode array in which the readout time per diode in array is 100 usec or less. For an optical system efficiency of 5% the required laser power would be about 2 mW, although this estimate of achievable efficiency may be optimistic. Increasing the number of inputs to be correlated requires that the readout time decrease as N^2 or that the detector saturation level increase in the same proportion. Furthermore, the required laser power increases as N^3, placing a more serious restriction on the practical number of inputs. For $N = 10$, using the data from the example, $(t/Nd) < 10$ usec and $Pl > 250$ mW are required, impractical with currently available devices.

If it is assumed that the mm-array is to be comprised of a Y shaped array of about 21 antennas, 7 per arm of the array, a total of 210 separate cross correlations must be continuously performed to sample all the available baselines. Thus, 210 dual input acousto-optic spectro-correlators would be required. A practical multiple input correlator would have $N < 4$, requiring $(t/Nd) > 30$ usec and $Pl < 25$ mW. With 6 cross correlations per spectrometer, 35 complete 4 input spectro-correlators would be required.

The mechanical stability requirements of such a system would appear to be comparable to those of a single input spectrometer. Although high performance single input units have been successfully constructed, they are still reported to suffer from residual problems associated with temperature dependent instabilities, stray light problems and generally are physically large. It would appear that the task of constructing and operating 35 or more acousto-optic spectro-correlators would present problems in terms of space requirements, system stability and reliability, especially since many delicate adjustments to the optical system are required in the setting up of such devices. An integrated optics approach would be highly desirable in terms of repeatability and stability. However, the current or near-term future technology in this field would severely limit the bandwidth and dynamic range obtainable in an integrated system. Neither form of cross correlating acousto-optic spectrometer has been demonstrated to be practically realisable.

It is therfore felt that the acousto-optic approach to the design of cross correlating spectrometer is not at present a practical proposition for the for the mm-array project. Developments over the next several years in very active field may make the integrated approach more practical.

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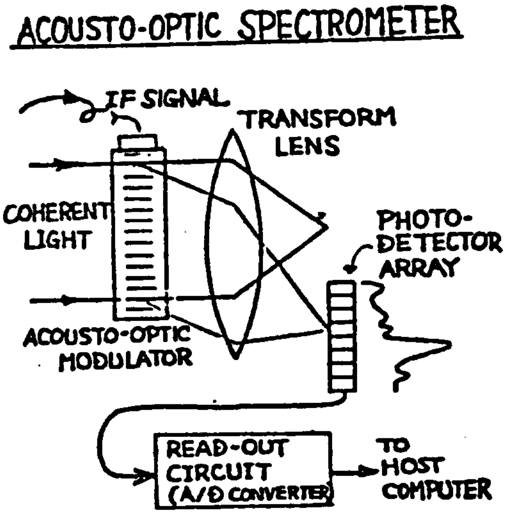

Figure 1.

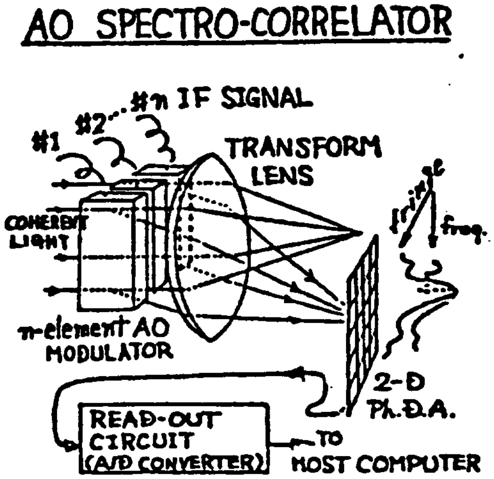

Figure 2.(a)

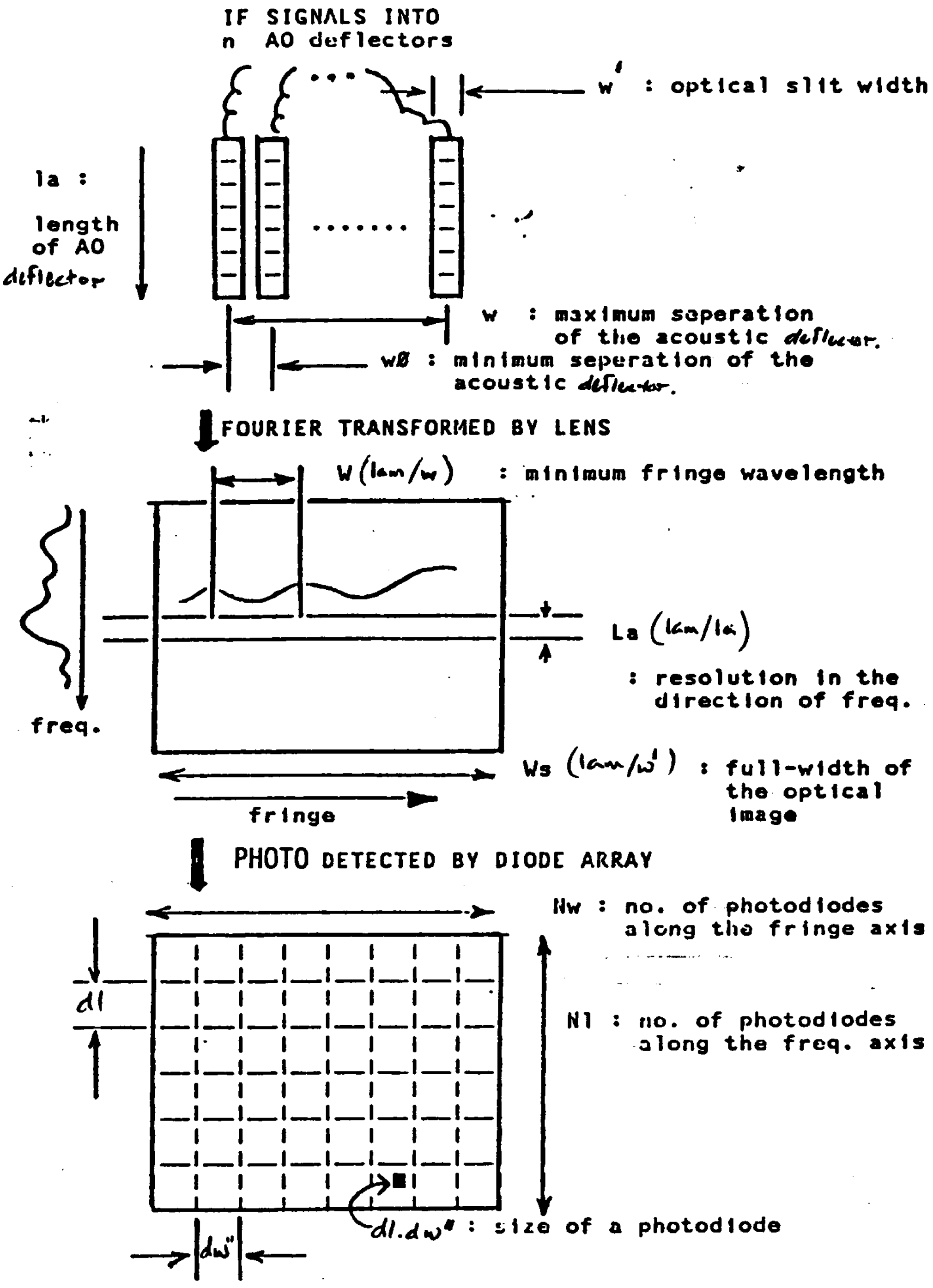

Figure 2(b) Notations for the acousto-optic spectro-correlator.