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FREQUENCY RESOLUTION OF AN ACOUSTO-OPTICAL SPECTROMETER

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Abstract: The paper discusses the frequency resolution of an acousto-optical spectrometer (AOS) system as affected by the acousto-optical deflector and the coherent light beam truncation ratio, and examines the response of the photodiode array reception system as affected by the AOS frequency resolution. The broadening of the resolution line pattern caused by the response of a photodiode pixel was computed. From this discussion, the authors proposed selection principles for AOS design parameters, including the light beam truncation ratio, focal length of the Fourier lens, and the number of photodiode array elements. These principles include the overall consideration of resolution, frequency bandwidth, and side lobes of the instrument profile in order to enable the AOS to be designed on a quantitative basis that is suitable to specific observational requirements. To verify these theoretical calculations, the frequency resolution was experimentally measured.

I. Introduction

AOS [acousto-optical spectrometer] have good features of design simplicity, low cost, reliable operation, high sensitivity, high time resolution, wide frequency coverage, and relatively high frequency resolution; therefore, AOS are finding growing use in radioastronomical observation. Observations of solar radio flares, over a wide frequency range from the meter waveband to submillimeter waveband, observation of molecular spectral lines, and pulsars and interstellar glittering, are the fields in which AOS have a role to play.

Frequency resolution is an important AOS parameter. In the observation of radio spectral lines, in particular, improved resolution is one of the main topics of AOS design. The frequency resolution of an AOS is determined mainly by the properties of the acousto-optical deflector (AOD), coherent light beam truncation ratio, and the response of the photodiode array (PDA) [1].

II. AOS Frequency Resolution, and Broadening of Resolution Line Pattern by the PDA

1. AOD resolution, side lobes, and the truncation ratio

The AOD window is a narrow rectangular opening. To uniformly distribute the light beam, based on Bragg diffraction relationship of acousto-optical interaction [2], light beam deflection caused by the supersonic frequency change δf:

$$\delta\theta = \frac{\lambda}{v}\delta f \tag{1}$$

in the equation, v is the velocity of supersonic propagation in the medium, and λ is the wavelength in the medium. The AOD frequency resolution is (it is defined as the theoretical resolution):

$$\delta f = \frac{v}{D} \tag{2}$$

In the general situation, the laser beam incident to the AOD aperture is the gaussian distribution. Assume that the beamwidth of the gaussian light beam $1/e^2$ is d_0, the truncation ratio $\rho = D/d_0$. The Fourier transform of the gaussian function is still a gaussian function; the distribution of diffraction light intensity is approximately the same as the gaussian distribution. The angle of light beam divergence of the equivalent Rayleigh criterion (the light intensity at the fringes is reduced to 40.5 percent of the light intensity at the center):

$$d\theta = \gamma \cdot \frac{\lambda}{D} \tag{3}$$

In the equation, γ is the field broadening coefficient. The AOD frequency resolution is:

$$df_{AOD} = \gamma \cdot \frac{v}{D} = \gamma \cdot \delta f \tag{4}$$

The value of γ is determined by the light beam truncation ratio, as shown in Fig. 1. The smaller ρ is, the smaller is γ, thus the higher the resolution. However, when ρ is too small, the light energy utilization rate will be too low. For astronomical observations, however, it is more important to have the side lobes of the resolution pattern as small as possible, in order to avoid signal confusion. For a $(\sin x/x)^2$ type distribution (corresponding to the case $\rho = 0$), the side lobes are -13db (the light intensity of the first side lobe is 0.047 times the light intensity of the main lobe). Randolph and Morrison computed the acousto-diffraction graphs of the gaussian aperture distribution under different truncation ratios [3]. Because of the truncation effect of restricted aperture size, side lobes appear in the diffraction graph. The smaller the truncation ratio, the larger the side lobes. Therefore, in selecting the truncation ratios, the effect of resolution magnitude and side lobe magnitude should be taken into account. For example, by selecting ρ approximately equal to 1.3, the side lobes will not be larger than -20dB (the side lobe magnitude is less than 1 percent of the main lobe), but the resolution γ is reduced by a factor of approximately 1.3.

2. Broadening of resolution line pattern with the PDA

The spatial response of PDA pixels can be approximately expressed in terms of a trapezoid function. Since the diffracted light can only illuminate a limited number of separate pixels, the contour of the AOD diffraction graph will be broadened (thinned) by the PDA. The frequency resolution of an

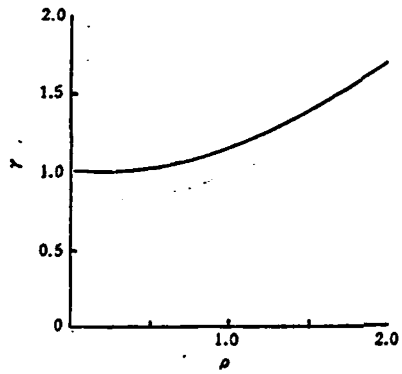

Fig. 1. Relationship between light beam field broadening coefficient and truncation ratio (see [3])

AOS system is the AOD resolution broadening by the PDA. The diffracted light intensity distribution outputted by the PDA is equal to the AOD diffraction graph contour plus the convolution of the PDA pixel response:

$$S(x_t) = \int_{\mathrm{Pixel}} P(x_t - x) Y(x) dx \tag{5}$$

In the equation, P(x) is pixel response; Y(x) is the distribution of the AOD diffraction light intensity; $S(x_t)$ is the relative output of the pixel; x_t is the position of the trapezoid geometrical center on the x-axis.

It is assumed that N PDA pixels are covered with the half-width of the AOD diffraction line pattern.

For fixed AOD and PDA, the value of N is determined by the magnitude of the Fourier lens focal length. The greater the focal length for a certain field angle, the larger the number N of pixels distributed and covered by the focal plane.

As N changes, this means a change in focal length of the Fourier lens and a change in the covering extent on the focal plane in terms of angular distribution. Without allowing for the absolute magnitude of focal length, calculation of the convolution is not related to the absolute magnitude of various dimensions.

The maximum value of Eq. (5) after AOD response to thinning caused by the PDA:

$$S_{max} = \int_{Pixel} P(x)Y(x)dx \qquad (6)$$

Determined by the thinning effect of the PDA, the broadening factor B_p of AOD spatial response can be derived through the above-mentioned numerical calculation of convolution.

Therefore, the frequency resolution of the entire acousto-optical spectrometer [AOS] system is:

$$df_{AOS} = B_p df_{AOD} = B_p \cdot \gamma \cdot \delta f \qquad (7)$$

The authors calculated the broadening factors of $(\sin x/x)^2$ type and gaussian type diffraction line patterns for the response of PDA pixels. The actual resolution line pattern lies between the two above-mentioned types. The smaller the truncation ratio, the closer is the line pattern to the $(\sin x/x)^2$ type. The larger the truncation ratio, the closer the line pattern is to the gaussian type. B_p is used to indicate the mean value of the broadening factors for the two line patterns. Fig. 2 shows the relationship curve between B_p and N.

From Fig. 2, when N = 1, the broadening factor B_p is 1.27. When N = 2, B_p is lowered to about 1.07. When N is larger than 2, the rate at which the broadening factor decrease slows down. Since a certain bandwidth should be maintained, when the value of N is selected to be high, the number of PDA pixels should increase, thus raising the cost. Therefore, generally N is chosen between 1 and 2. For example, by selecting N equal to 2, the broadening factor is in the vicinity of 1.07; the lowered frequency resolution is acceptable. When high resolution is not required, such as the case when AOS is used to solar radio flares, it is relatively economically to select N = 1 [4].

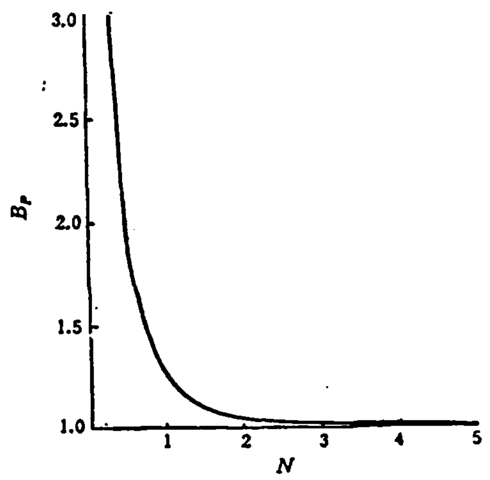

Fig. 2. Broadening of resolution line pattern due to PDA

3. Selection of focal length of Fourier lens

Within the variation δf of signal frequency, the change in the light beam deflection angle in the acousto-optical crystal is derived by means of Eq. (1).

For a given pixel number N covered by the half-width, the focal length of the lens is:

$$F = \frac{Nbv}{\lambda_0 \delta f} \tag{8}$$

In the equation, λ_0 is the laser wavelength in vacuum; δf is the theoretical resolution of AOD; b is pixel spacing.

In principle, the frequency bandwidth of the AOS is determined mainly by the working bandwidth of a given AOD. In practice, since the number of PDA pixels as a commercial product is divided into predetermined levels, with a predetermined focal length of the lens, the designer can select only a pixel number such that in a commercial PDA product to approximately satisfy the AOD bandwidth; thus, the effective bandwidth of the instrument is somewhat limited. Actually, the focal length of the lens should also be determined by taking all the above factors into account.

III. Comparison Between Measurement and Theoretical Computation of AOS Frequency Resolution

By adopting a Fourier lens with a long focal length, the relative resolution capability of PDA pixels is higher, the number of pixels occupied by the response of the AOS single-frequency signal is higher, and thus the half-width resolution can be measured more precisely. By measuring the number of PDA pixels occupied by the half-width of a single-frequency signal response, the AOS resolution can be derived.

Fig. 3 shows an experimental AOS light path diagram. The light beam from the laser source passes through a polarizer to adjust the light intensity before incident into the lens beam expander. The direction of propagation of the expanded beam forms an angle with the incident light beam. After being reflected at a reflecting mirror, the light beam direction is deflected; thus, the layout of the various elements is relatively compact. The light beam diffracted with the AOD passes through a lens to focus on the PDA. The output of these pixels is monitored by an oscillograph. The entire system is installed on a shock-absorption platform.

1. Measurement of frequency width of PDA pixel

The focal length of the lens used is 1455mm. By adjusting the single-frequency signal input to the AOD transducer, the peak value of signal response falls successively on the pixels at the two PDA terminals, then the difference between two signal frequencies is the total frequency bandwidth of the PDA. By sampling three sets of PDA pixels with ten samples per set, the statistical mean values are derived. The error is expressed in terms of the standard error of the mean from sampling three sets.

Δf = (10.65 plus or minus 0.03) MHz

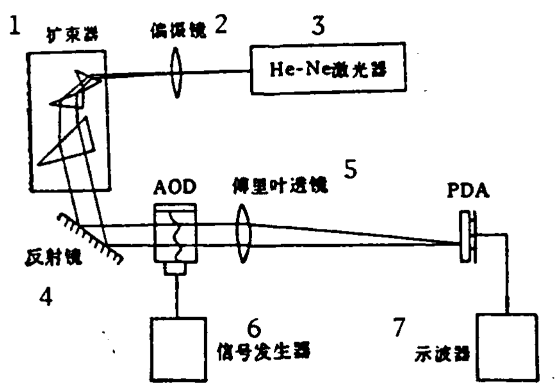

Fig. 3. Experimental AOS block diagram
KEY: 1 - Beam expander 2 - Polarizer 3 - He-Ne laser 4 - Reflecting mirror 5 - Fourier lens 6 - Signal generator 7 - Oscillograph

The number of PDA pixels used is 1024; the frequency width of each pixel is:

$$df_p = \Delta f/1024 = (10.40 \text{ plus or minus } 0.03) \text{ kHz}$$

2. Measurement of resolution

The authors obtained resolution values at several frequencies from the number of pixels covered by the half-width of single-frequency signal response at three frequencies: 38MHz, 43MHz, and 48MHz. At the signal input power of 20mW, the light intensity is changed to adjust to the output amplitude. The Bragg angle is fixed to an optimal frequency response. By using an adjustable oscillograph, each grid square on the fluorescent screen is matched to a pixel. When the peak value of the resolution line pattern falls onto a certain pixel, one can read off from the fluorescent screen, the number of pixels N_0 covered by the half-width. By making several pixel measurements while the peak values are varied, three sets of samples are taken at each frequency to find the statistical mean.

The half-width resolution is

$$df = N_0 df_p \tag{9}$$

Table 1 lists the results of experimental measurements of resolution.

TABLE 1. Measurement of Resolution of AOS Frequency

f(MHz)	N_0	df (kHz)
38	4.12±0.08	42.8±0.9
43	4.19±0.09	43.6±0.9
48	4.23±0.09	44.0±0.9

As discovered in experiments, resolution at high frequencies is lower than the resolution at low frequencies. This is because the supersonic attenuation increases with increasing frequency, so that resolution at high frequencies is somewhat less.

3. Comparison with calculated resolution

In the TeO_2 AOD crystals used by the authors, the effective aperture is 20mm, the supersonic speed is 650m/s. Therefore, the theoretical resolution (Rayleigh criterion) of the AOD is

$$\delta f = v/D = 32.5\text{kHz}.$$

The truncation ratio of the expanded light beam is $\rho = 1.54$. From Fig. 1, the line pattern broadening due to the gaussian distribution is $\gamma = 1.44$.

At a center frequency 43Mhz, the number of pixel N_0 covered by the half-width was measured experimentally and found to 4.19 (refer to Table 1). From Fig. 2, it is seen that the broadening factor of the corresponding PDA $B_P \doteq 1.012$ (corresponding to $N \doteq 4.14$).

For the diffraction line pattern of the uniformly distributed incident light, that is, the $(\sin x/x)^2$ type, the ratio between the half-width resolution and the Rayleigh resolution is:

$$\gamma_{HR} = 0.886$$

Therefore, the AOS half-width resolution is:

$$df = \gamma_{HR} \cdot \gamma \cdot B_P \cdot \delta f \tag{10}$$

When calculated, df = 42.0kHz. When measured experimentally, the resolution at 43MHz is 43.6kHz; this basically agrees well with the calculation.

The coma aberration caused by an unsymmetrical optical path system, and the spherical aberration occurring at imaging of a monochromatic pencil beam can diminish the resolution. In addition, the optical inhomogeneity of the crystal and attenuation of the supersonic wave when propagating in the crystals also have an effect on the resolution.

IV. Conclusions

1. The frequency resolution of an AOS is determined by AOD properties, the truncation ratio of the coherent light beam, as well as the interaction between the PDA pixel response and the convolution of the AOD single-frequency light pattern.

2. The smaller the truncation ratio of the light beam, the smaller is the effect on resolution. However, the result will be an increase in the side lobes of the instrument profile, thus affecting the quality of observation. Therefore, the selection of the light beam truncation ratio should comprehensively take into account the magnitudes of resolution and profile side lobes. The truncation ratio can be selected by changing the beam expansion increment.

3. The higher the number of PDA pixels that are covered by the instrument profile, the smaller is the effect on resolution due to PDA pixel response. However, in this way the width of the PDA reception frequency band becomes smaller. Therefore, overall consideration is required when selecting the instrument bandwidth and resolution based on the principal applications of the AOS.

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