Simulation analysis and implementation of spectral dispersion system based on virtually imaged phased array*

YANG Dan (杨丹)**, **LIU Jin-tao** (刘金涛), **FAN Xue-ke** (樊雪珂), **ZHU Wai-hui** (朱外辉), **WANG Shuai** (王帅), **and SONG Xiao-quan** (宋小全)

College of Information Science and Engineering, Ocean University of China, Qingdao 266100, China

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Virtually imaged phased array (VIPA) has the advantages of insensitive to polarization, simple structure and high in spectral resolution. Compared with commonly used dispersive devices, such as diffraction gratings or Fabry-Pérot (FP) interferometers, VIPA is self-aligned and has high transmission efficiency. In this paper, the dispersion mechanism of the VIPA is introduced in detail, the influence of incident angle and VIPA thickness on the dispersion performance near 532 nm is calculated and analyzed with MATLAB. According to the calculated results, the selected VIPA device has a thickness of 6 mm and an incident angle of 4°. The spectral dispersion system, in combination with corresponding optical devices, is designed and simulated with ZEMAX, then the experimental system was built. The spectral dispersion system based on VIPA, at a central wavelength of 532 nm, has the free spectral range of 15.08 GHz and the spectral resolution of 0.87 GHz. The system designed in this paper can be applied to high-resolution spectral detection such as Brillouin scattering, Raman scattering, laser fluorescence, laser-induced plasma and so on.

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In the classical spectral system, the diffraction grating and Fabry-Pérot (FP) interferometer are often used as dispersion devices[1,2]. In 1996, Shirasaki M[3] proposed the virtually imaged phased array (VIPA), which has the advantages of polarization insensitivity, simple structure, and high in spectral resolution. Compared with the diffraction grating which requires high precision engraving, virtual light sources are "self-aligned" in VIPA, and the quality of the interference pattern depends only on the fineness of the VIPA. Compared with the FP interferometer, the incident surface of VIPA is nearly 100% reflective coating. The limited size and finite angular spread of the beam allow most of the incident light energy to be transmitted to the detector, thus the optical efficiency of VIPA is about 60%[4]. At present, VIPA is mainly used in optical communication, pulse compression, middle infrared gas measurement, femtosecond pulse shaping, and so on[5-11].

In the past, the research on VIPA mainly analyzed its characteristics in the infrared band around 1 550 nm, and applied it to the fields of wavelength division multiplexing and dispersion compensation. This paper is aimed at its characteristics at around 532 nm. The system designed in this paper will be used in high-resolution spectral detection such as Brillouin scattering and Raman scattering. In this paper, the dispersion mechanism of VIPA is introduced in detail, and the influence of the incident angle and VIPA thickness on the dispersion performance near 532 nm is calculated and analyzed with MATLAB software. According to the analysis results, the specific VIPA and corresponding optics were selected to build a VIPA-based spectral dispersion system. Then the ZEMAX software was used to simulate the dispersion characteristics of the system and the experimental measurements were carried out.

The dispersion mechanism of VIPA is similar to that of FP interferometer. As shown in Fig.1, VIPA can be regarded as a glass plate, which the incident surface is a total reflection coating, and the exit surface is a high-reflection coating of about 95%. The incident parallel light passes through the cylindrical lens to form a line beam, and converges on the exit surface of the VIPA. A part of the incident light beam is transmitted from the exit surface, and most of the light is reflected inside the plate, and a part of the light is emitted from the exit surface each time it is internally reflected, and the process is repeated continuously. Multiple reflections of the incident beam within the plate can be seen as forming a series of virtual light sources, each having a fixed phase difference, and is therefore called as a virtually imaged phased array[12,13].

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** E-mail: yangdan@stu.ouc.edu.cn

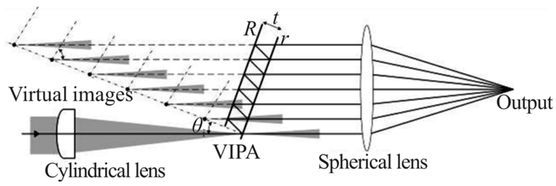

Fig.1 The schematic diagram of VIPA

Assuming that the Gaussian beam is incident, the intensity envelope of the beam should be a function of exponential descent for the nth virtual source[14-17]:

$$E_n(y)=(Rr)^n\left(-\frac{(y-\Delta y_n)^2}{\frac{(\lambda f_c)^2}{(\pi W)^2}}\right), \quad (1)$$

where R is the reflectivity of VIPA incident surface, r is the reflectivity of VIPA exit surface, y is the distance between the point on the imaging surface and the center point, λ is the central wavelength, f_c is the focal length of cylindrical lens that used to compress the beam before it enters the VIPA, and W is the spot size of incident beam before the cylindrical lens.

Using Fresnel diffraction analysis, the intensity distribution can be obtained as

$$E_{\mathrm{out}_n}(y,\lambda)\propto \exp\left[-\mathrm{i}\frac{k}{2f}\left(1-\frac{t}{f}\right)y^2\right]\times \int_{-\infty}^{+\infty}E_n(x)\exp\left(\frac{\mathrm{i}ky}{f}\right)\mathrm{d}x, \quad (2)$$

where f is the focal length of spherical lens after the beam exits, k is the wave vector, and t is the thickness of VIPA. Suppose that there are an infinite number of virtual light sources, the intensity distribution can be written as

$$E_{\mathrm{out}}\propto \exp\left(-\frac{f_c^2y^2}{f^2W^2}\right)\times \frac{1}{1-Rr\exp\left(-\mathrm{i}\frac{4\pi t\cos(\theta_i)}{\lambda}+...\mathrm{i}\frac{4\pi t\sin(\theta_i)y}{\lambda f}+\mathrm{i}\frac{4\pi t\cos(\theta_i)y^2}{\lambda f^2}\right)}, \quad (3)$$

where θ_i is the incident angle at which the beam is incident on the VIPA. Thus the light intensity can be obtained as:

$$I_{\mathrm{out}}(y,\lambda)\propto \exp\left(-\frac{2f_c^2y^2}{f^2W^2}\right)\times \frac{1}{(1-Rr)^2+4Rr\sin^2\left(\frac{k\Delta}{2}\right)}. \quad (4)$$

Ideally, the angular dispersion factor of a VIPA-based spectral dispersion system can be expressed as[18]

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda}=-\frac{1}{\lambda_0\left(\tan(\theta_i)+\frac{y}{f}\right)}. \quad (5)$$

The spectral resolution ($FWHM$) can be expressed as[12]

$$FWHM=\frac{\lambda_0^2}{2\pi nt\cos(\theta_i)}\frac{1-Rr}{\sqrt{Rr}}. \quad (6)$$

The interference phase matching equation can be written as:

$$k\Delta=k\left[2t\cos(\theta_i)-\frac{2t\sin(\theta_i)y}{f}-\frac{t\cos(\theta_i)y^2}{f^2}\right]=2m\pi. \quad (7)$$

Therefore, the free spectral range (FSR) can be expressed as[13]:

$$FSR=\frac{c}{2t\cos(\theta_i)-\frac{2t\sin(\theta_i)y}{f}-\frac{t\cos(\theta_i)y^2}{f^2}}. \quad (8)$$

It can be seen from Eq.(5) that the angular dispersion factor of VIPA is inversely proportional to the angle of incidence. For an incident angle of 4°, the VIPA angular dispersion factor of fused silica is approximately 21.4, while the angular dispersion factor of the same size diffraction grating is 7.5. The smaller the angle of incidence, the larger the obtained angular dispersion, but the angle of incidence should have a minimum value, below which the incident beam will be obscured by the high reflection window. Therefore, in the overall design process of the dispersion system, the incident angle and VIPA thickness should be carefully analyzed to obtain the most suitable spectral resolution.

It can be seen from Eqs.(5)—(8) that in the parameters of the spectral dispersion system based on VIPA, R and r can be basically determined by the coating process, and the main factors affecting the dispersion characteristics of VIPA are the incident angle θ_i and the thickness t. According to the parameters of Tab.1, the influence of incident angle and VIPA thickness on spectral resolution is simulated by MATLAB software at a central wavelength of 532nm, and the simulation result is shown in Fig.2.

It can be seen from Fig.2 that the spectral resolution is increased by about 0.007 pm (7.4 MHz) when the incident angle is increased from 2° to 10°, and the spectral resolution is reduced by about 1.36 pm (1 440 MHz) when the thickness is increased from 1 mm to 7 mm. With the increase of VIPA thickness, the loss of beam in VIPA will increase, and the number of light spots will also increase, which will affect the interference results. Therefore, in order to obtain a certain dispersion effect, the incident angle and thickness of the VIPA should be integrated. In the dispersion system designed in this paper, the incident angle is chosen to be 4° and the thickness of VIPA is 6 mm.

According to the parameters in Tab.1 and Eq.(4), the intensity distribution of spectral dispersion system based on VIPA can be obtained as shown in Fig.3. It can be seen from Fig.3 that the light field is distributed periodically, and for the same wavelength, different bright spots represent different diffraction order[19]. Calculated by Eq.(8), the FSR of the whole dispersion system is about 15.08 GHz, the spectral resolution ($FWHM$) is about 0.87 GHz, the distance between adjacent diffraction orders is about 0.4 mm, and the fineness is about 17.4. It can be seen that the characteristics of the dispersion system we designed in this paper are higher than those of the general optical dispersion devices[20].

Tab.1 Parameters of simulation system

Parameters	Value
Spot size of incident beam W (mm)	5
Focal length of cylindrical lens f_c (mm)	500
Focal length of spherical lens f (mm)	500
Reflectivity of VIPA incident surface R	100%
Reflectivity of VIPA exit surface r	95%
Center wavelength of incident beam λ_0 (nm)	532

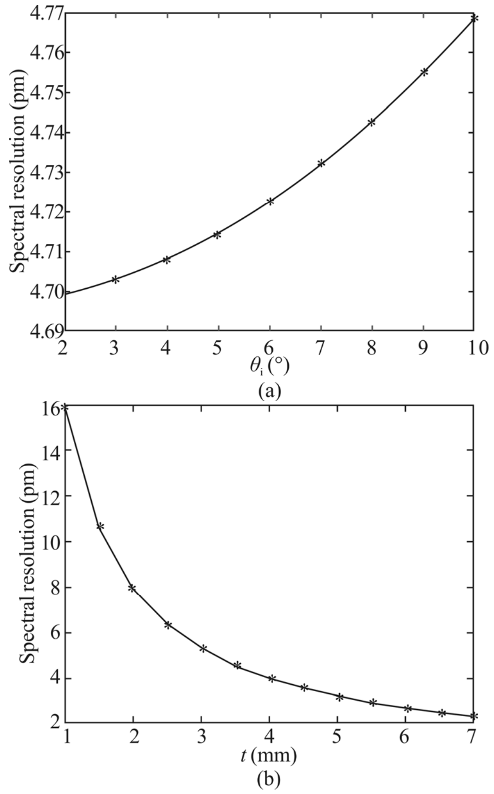

Fig.2 (a) Relationship between incident angle and spectral resolution and (b) Relationship between VIPA thickness and spectral resolution

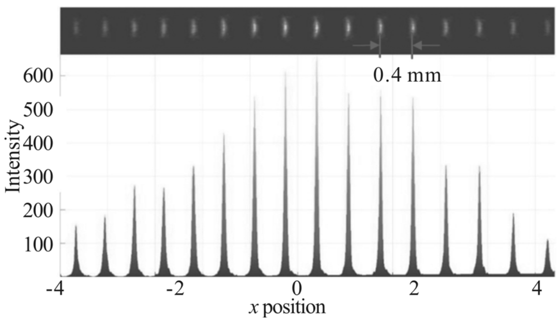

Fig.3 Intensity distribution of high resolution spectral dispersion system based on VIPA

ZEMAX software has powerful optical design and simulation analysis function, which can trace the light through sequence and non-sequence modes to optimize the designed system.

Combined with the parameters in Tab.1, the system is simulated and analyzed by ZEMAX software. The system model is shown in Fig.4. The simulation model uses a Gaussian light source as the input source(λ_0=532 nm), which is collimated and expanded into a parallel light by a combination of lenses (first: 5 mm, second: 50 mm), and then becomes a line beam through a cylindrical lens(f_c=500 mm), and is focused and coupled to reach the exit window of the VIPA. Set the interval between the cylindrical lens and VIPA as a variable to optimize the spot size in the y direction. Using the ZEMAX nesting mode, the reflectivity of the front and back surfaces of the VIPA is set to 99.9% and 95%, the incident angle is 4°, and the thickness is 6mm. The line beam is repeatedly reflected and transmitted between the front and back surfaces of the VIPA. The transmitted light interferes with each other after passing through the spherical lens (f=500 mm), and finally reaches the detector for imaging. As shown in Fig.5, the distance between adjacent diffraction orders is about 0.42 mm.

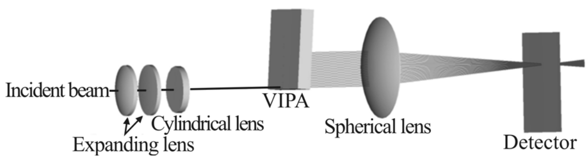

Fig.4 ZEMAX simulation model of high resolution spectral dispersion system based on VIPA

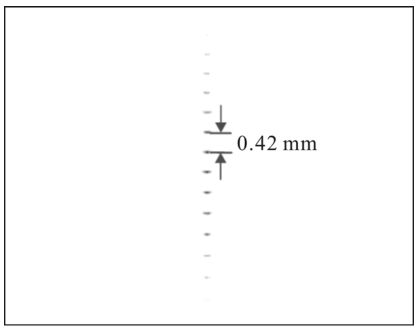

Fig.5 ZEMAX simulation imaging results of high resolution spectral dispersion system based on VIPA

According to the above principles, and exactly the same parameters as used in the simulation system. The spectral dispersion system based on VIPA is built and verified by experiments. The structure of the experimental system is shown in Fig.6. The laser model is Melles Griot 05-LGR-025, the central wavelength of the incident light is 532 nm, the incident angle is 4°, the thickness of VIPA is 6 mm, the detector model is ICX285AL, and its pixel size is 6.45 μm×6.45 μm.

The experimental results are shown in Fig.7. The distance between adjacent diffraction orders is about 0.42 mm. It can be seen that the spectral dispersion system based on VIPA is high in spectral resolution. Within the allowable range of error, the experimental results are basically consistent with the simulation results, thus verifying the accuracy of simulation analysis, device selection and system experiments.

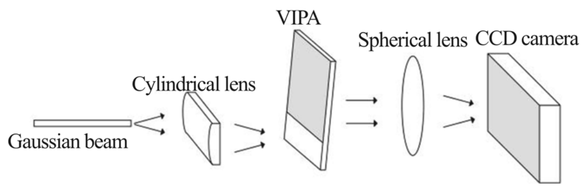

Fig.6 Experimental structure diagram of high resolution spectral dispersion system based on VIPA

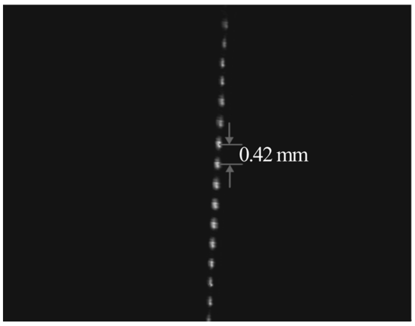

Fig.7 Experimental result of high resolution spectral dispersion system based on VIPA

In summary, we analysis the dispersion mechanism of the VIPA in detail, and the influence of incident angle and VIPA thickness on the dispersion performance near 532 nm is calculated and analyzed with MATLAB software. The simulation results of ZEMAX model are established with the corresponding optics, and the spectral dispersion system based on VIPA is built in the laboratory. Within the allowable range of error, the experimental results are basically consistent with the simulation results, thus verifying the accuracy of the experiment. The VIPA-based spectral dispersion system designed in this paper has the free spectral range of about 15.08 GHz and the resolution of about 0.87 GHz. It can be seen that this dispersion system we designed is high in resolution and has broad application prospects in the fields of spectral imaging and processing. It can be applied to high-resolution spectral detection such as laser Brillouin scattering, Raman scattering, laser fluorescence, laser-induced plasma and so on.

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