Study on the characteristics of novel optical phased array based on wave-guide

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Abstract: A novel scheme of optical phased array (OPA) based on wave-guide was represented in this paper. Fiber paths was main design of system, the single mode fibers were used as transmission paths, photonic crystal fibers (PCF) were adopted as the output array, $LiNbO_3$ wave-guide was used as the phase modulator. The system configuration was given, performance of main device such as $LiNbO_3$ wave-guide and PCF array were analyzed. According to the theory of OPA and electro-optical effect of $LiNbO_3$ wave-guide, the feasibility of system had been demonstrated. By adjusting the phase shift of each $LiNbO_3$ wave-guide, the beam deflection had been observed. Simulation experiments had been implemented to study the influence of its structure parameter on output diffraction characteristics. The results show that the inter-elements distance, the quantity of fiber core and arrangement of fiber core affect the beam scanning quality including Full Width at Half-Maximum (FWHM), output intensity distribution.

Key words: OPA; PCF; $LiNbO_3$ wave-guide; beam steering

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一种新型的光波导光学相控阵的特性研究

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摘 要: 采用光纤作为传输链路,将光子晶体光纤作为系统的输出阵列,$LiNbO_3$ 波导作为相位调制器,构建了一种基于光纤光路的光波导光学相控阵。根据光学相控阵理论和 $LiNbO_3$ 波导的电光效应,分析了系统的可行性, 并研究了这种新型结构下的光波导光学相控阵的输出衍射特性和光子晶体光纤阵列结构参数的关系。研究结果表明通过控制施加在 $LiNbO_3$ 波导上的电压可以改变出射光束的附加相位从而实现光束的偏转;光子晶体光纤阵列上的纤芯数量、纤芯间距以及纤芯的排列方式等结构参量会对系统的输出光束的光强分布、半峰值全宽度(FWHM)和归一化的振幅分布产生影响。随着光子晶体光纤制作工艺的不断发展,系统的光束扫描质量将会逐渐提高并且色散特性和传输特性将会获得改善,为今后这种光学相控阵系统的设计提供了理论基础和技术依据。

关键词: 光学相控阵; 光子晶体光纤; 铌酸锂波导; 光束控制

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0 Introduction

Optical phased array (OPA)[1] have been a new beam steering technology which is offering precise stabilization random−access pointing, programmable multiple simultaneous, OPA originated from the microwave radar which can be seen as the optical simulation of microwave phased array[2]. By controlling the voltage of each array elements, the additional phase of light beam will be changed to realize the deflection of the beam. Now the research on OPA is mainly in liquid crystal material [3], piezoelectric ceramic materials[4] and wave−guide material[5−6]. The modulation rate of piezoelectric ceramic is fast, but the driving voltage is too high to reach the two thousand volt. The advantage of liquid crystal material is low driving voltage, flexible scanning method and easy formation. However, long response time and non−stable performance is still required to promote. Compared with the piezoelectric ceramic materials and crystal material, wave−guide material has comprehensive properties, for its low driving voltage and short response time. So it has important value on the study of wave−guide OPA. Current research on wave−guide OPA was mainly based on the regular OPA theory, the inter−element distance [7] is hard to be reduced to a ideal state which has limited the quality of the beam steering [8]. Now the research was concentrated on how to narrow the inter−elements distance to enhance the accuracy of beam scanning.

We proposed a novel OPA system based on $LiNbO_3$ wave−guide[9], optical paths[7] is main design of system, the optical fibers are used as transmission paths, photonic crystal fibers (PCF)[10] are adopted as the output array, $LiNbO_3$ wave−guide [11] is used as the phase modulator. Compared with traditional fiber array, the inter−elements distance [12] in the PCF can be compressed to one−tenth or less. The optical fiber was used as the transmission path for its low loss and good anti−interference performance of light transmission. $LiNbO_3$ wave−guide is the phase modulator to modulate the phase of beam in each optical path respectively. Then the beam was coupled with PCF, finally emitted from the fiber array. By controlling the voltage on the wave−guide, we can change the additional phase of the light wave to realize the beam steering. In this system, optical fiber path can effectively improve the speed of light beam, PCF array can achieve the one−dimension [13] or two−dimension scanning by controlling the arrangement of the fiber core array. As for this system we propose above, the theoretical analysis and simulation have been done, the feasibility of this system [14−15] was tested and the simulation experiments was also conducted to study the influence on beam scanning when the structure of the fiber core was changed.

1 Fundamental principle of the wave−guide OPA

We use the periodic grating diffraction equ ation to analyze the basic principle of wave−guide OPA. as shown in Fig.1. The N−tier wave−guide control the light respectively, when the ideal light wave perpendicular incident upon the wave−guide array.

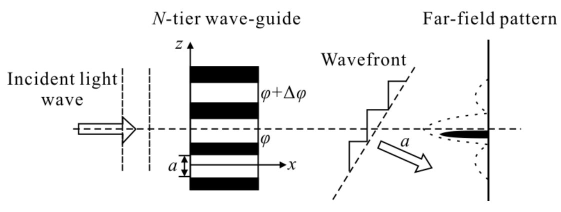


Fig.1 Schematic diagram of OPA

While there is no additional phase [6], the diffraction amplitude of output light is expressed by:

$$\widetilde{E}(p)=C(1+e^{i\varphi}+e^{i2\varphi}+\cdots+e^{-i(N-1)\varphi})\int_{-a/2}^{a/2}e^{-ikz_1\sin\theta}\mathrm{d}z_1 q \quad (1)$$

The light intensity is given by:

$$I(P)=I_0\left(\frac{\sin\alpha}{\alpha}\right)^2\left(\frac{\sin(N\varphi/2)}{\sin(\varphi/2)}\right)^2 \quad (2)$$

where $\alpha=ka\sin\theta$, $\varphi=(2\pi/\lambda)d\sin\theta$, α is thickness of wave−guide, d is the inter−element distance, θ is the diffraction angle, λ is wavelength.

When the additional phase exist, the phase delay in adjacent wave-guide is $\Delta\varphi$, the diffraction amplitude of output light can be expressed by:

$$\widetilde{E}(p)=C(1+e^{i(\varphi-\Delta\varphi)}+e^{i2(\varphi-\Delta\varphi)}+\cdots+e^{-i(N-1)(\varphi-\Delta\varphi)})\int_{-a/2}^{a/2} e^{-ikz_1\sin\theta}\mathrm{d}z_1(1) \quad (3)$$

The light intensity is given by:

$$I(P)=I_0\left(\frac{\sin\alpha}{\alpha}\right)^2\left(\frac{\sin(N(\varphi-\Delta\varphi)/2)}{\sin((\varphi-\Delta\varphi)/2)}\right)^2 \quad (4)$$

We can find that when different voltage is added on the wave-guide, the light beam will produce different phase delay, then the difference can conduct the radiation pattern removed to realize beam steering. It's fundamental principle of the wave-guide OPA.

2 System configuration

The configuration of the new wave-guide OPA system is illustrated in Fig.2. $LiNbO_3$ wave-guide

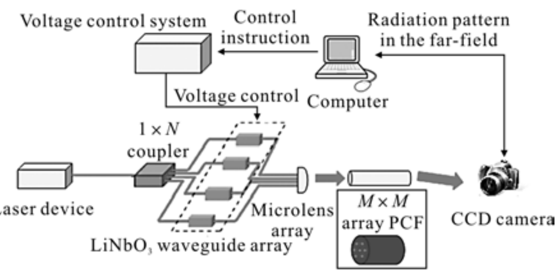


Fig.2 Configuration of OPA system

arrays and PCF array are the key devices of the system. A LD-pumped laser [7] with a wavelength of 1.55 μm is used as the light source. In the experiment, the light is split into fibers by a $1\times N$ polarization-maintaining couple, then the $LiNbO_3$ wave-guide which is inserted between couple and emitting array in each optical path will modulate the light beam on the control of the voltage control system according to the desired angle, then the modulated light is coupled into the PCF, later emitted. CCD camera captures the radiation pattern in the far-field, then send the data to the computer. By processing the image data, the computer provides the feedback to the voltage control system, then the system makes $LiNbO_3$ wave-guide generate the desire phase, after repeatedly adjustment and optimization, the light beam is deflected to the desire angle.

$LiNbO_3$ wave-guide phase modulator is a ideal optical phase modulator, as shown in Fig.3, because of the electro-optical effect [9] of the $LiNbO_3$ wave-guide, electrode is inserted in the two sides of the wave-guide, the SiO_2 buffer layer is set between the wave-guide and electrode to decrease the loss of light. Under extra electric field, refractive index of wave-guide will be changed to modulate the phase of light beam.

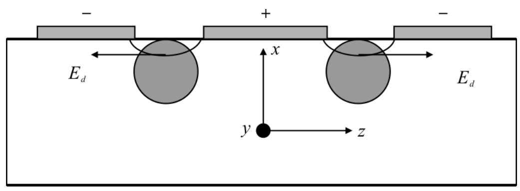


Fig.3 Configuration of $LiNbO_3$ wave-guide electrode

When the voltage is added in the wave-guide, the change of refractive index is given by:

$$\Delta n_z=\Delta n_e=\frac{1}{2}n_e\gamma_{33}E \quad (5)$$

In order to solve the problem that the electric field and optical field is not homogeneous, we bring the mode field overlap factor $\Gamma(\Gamma=\frac{G}{V}\iint E|E'|^2\mathrm{d}A)$, so the refractive index can be given by:

$$\Delta n_e=\frac{n_e^3\gamma_{33}V\Gamma}{2G} \quad (6)$$

G is distance between two electrode. When the length of electrode is L, the phase change of the wave-guide is expressed by:

$$\Delta\varphi=\Delta\beta L=\frac{n_e^1\gamma_{33}VL\Gamma\pi}{G\lambda} \quad (7)$$

PCF with a periodic transverse micro-structure have been in practical existence as low-loss wave-guide. Its internal structure is shown in Fig.4, it has excellent optical properties in some important ways such as dispersion, bire-fringence, non-linearity [10]. The fiber core of PCF is the line defect made by air hole or quartz material, and the cladding is photonic band gap structure composed of air hole which is arranged by different style. The light beam within certain wavelength is limited in the fiber core. Each fiber core can be seen as a standalone wave-guide, so the light beam with different phase can spread in different fiber core.

The distance between the fiber core can be one-tenth of the traditional fiber array, and coupling between each fiber core can only change the intensity distribution, in which the single-mode transmission will not be affected.

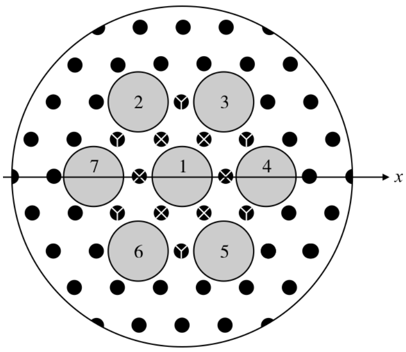


Fig.4 Profile of PCF

In the ideal situation, in the case that the transmission function of modulated light is $T(x)$, when passing the PCF array, the transmission function of single fiber core is $C(x)_k$, we give each light beam an additional phase by controlling the voltage on the wave-guide, so the phase difference of adjacent elements is given by:

$$\phi=\varphi+\Delta\varphi=\frac{2\pi}{\lambda}d\sin\theta+\Delta\varphi \tag{8}$$

The transmission function of single elements is:

$$C(x)_k=\exp(ik(\Delta\varphi+\frac{2\pi}{\lambda}d\sin\theta)) \tag{9}$$

So the transmission function of emergent light is:

$$T(x)=\sum_{k=0}^{N-1}\mathrm{rect}\left(\frac{x-kd}{a}\right)C(x)_k \tag{10}$$

a is width of fiber core, d is inter-elements distance, N is quantity of fiber core, $E(x)$ is amplitude distribution of far-field which can be given through the Fourier transform of $T(x)$:

$$E(x)=FT\{T(x)\} \tag{11}$$

The intensity distribution is:

$$I=E(x)\cdot E^*(x) \tag{12}$$

3 Simulation and analysis

Combined with the theory analysis and system design, and considering current technical lever, when the fiber core is at different arrangement, we use MATLAB to analyze the output diffraction characteristics and other performance include intensity distribution, normalized amplitude distribution, Full Width at Half Maximum (FWHM) when the fiber core is in one-dimension arrangement, as shown in Fig.5, N is number of the fiber core, a is width of the fiber core, d is the inter-elements distance, L is the electrode length of $LiNbO_3$ wave-guide, $\Delta\varphi$ is phase difference of adjacent elements.

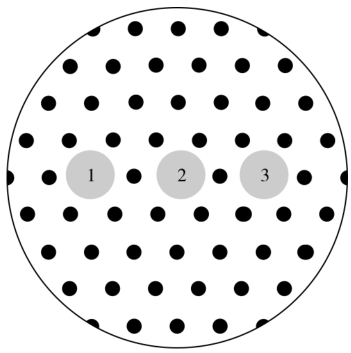


Fig.5 One-dimension arrangement

In order to achieve single-mode and low-loss transmission, the wavelength is 1 550 nm, we supposed that N=10, a=3 μm, d=10 μm, L=5 mm, when $\Delta\varphi$=0 and $\Delta\varphi$=1 rad, the output intensity distribution is shown in Fig.6, from which we can see that the light beam deflect 2° when $\Delta\varphi$=1 rad. So we can change the voltage to get different phase difference to realize the beam scanning.

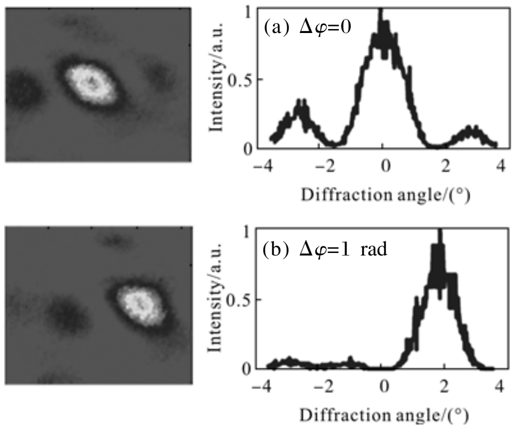


Fig.6 Influence of additional phase difference on the light intensity

As for OPA system, FWHM of main lobe is an important characteristics, it can describe the scanning precision of beam. If the numerical value of FWHM is smaller, the scanning precision is higher. We supposed that a=3 μm, d=12 μm, L=5 mm, and N is changed from 3 to 18, through the MATLAB, the simulation results is shown in Fig.7.

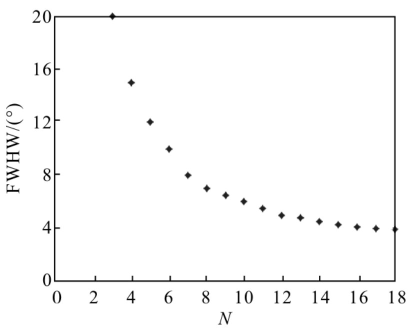


Fig.7 Relation of FWHM versus N

The picture shows that FWHM increases with the decrease of N, it mean that when the quantity of fiber core increase, the width of main lobe change smaller, the scanning precision will improve. It fit the theory of OPA.

Based on theory of OPA, it's known that inter-elements distance can affect intensity and quantity of grating lobe, then the scanning scope is also affected too. According to the grating diffraction theory, the condition for emergence of grating lobe can be given by:

$$\sin\theta_m=\pm\frac{\lambda}{d}m \tag{13}$$

It can be seen from Eq. (13) that with the increase of d, the period of grating lobe is shorter and the quantity of grating lobe increases which reduces the quality of beam scanning. In the simulation experiment, we supposed that a=3 μm, N=10, L=5 mm, then d=5 μm d=10 μm and d=20 μm.

The result is shown in Fig.8, from which we can see from the picture that when d is increased from 5 μm to 20 μm, the amount of the gating lobe significantly increases, and the intensity of grating lobe increases also so that it will disperse the energy of main lobe which lead to the decrease of the scanning scope and scanning quality. So from the perspective of application, the inter-elements distance should be reduced to restrain the grating lobe. The inter-elements distance for traditional fibers array are hard to be narrowed to such a small range for the obstacle in fabrication, the PCF array make it possible, and

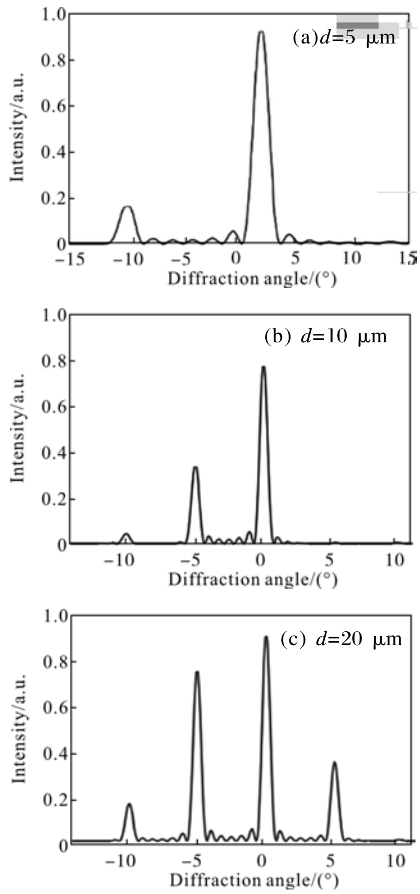


Fig.8 Influence of d on the light intensity

with the development of technology, the inter-elements distance for PCF array might be smaller to be applied for beam steering.

When the structure of fibers core is changed, as shown in Fig.9, based on the theory of PCF, the structure of the fiber core is closely related to the coupling strength, changing the air hole size or distance can realize the adjustment of coupling strength. We use the beam propagation method(BPM) to simulate the coupling characteristic of PCF along with the change of inter-elements distance.

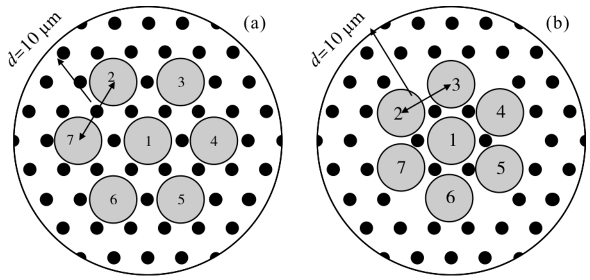
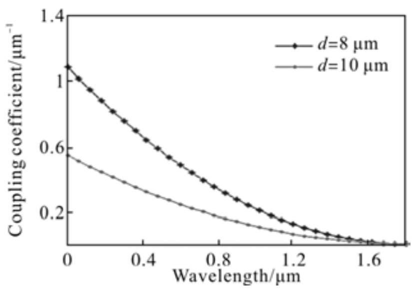


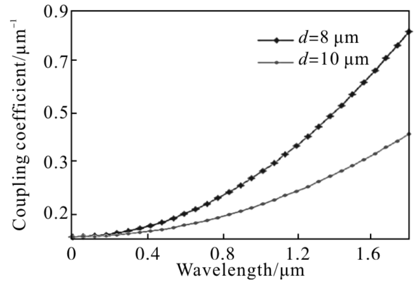
Fig.9 Two different arrangement of fiber core

We supposed that the material index n_e=1.47, the air hole diameter a=2 μm, wavelength λ=1.55 μm. We analyze the influence of changeable inter-elements distance on the coupling coefficient and the coupling length, the results is shown in Fig.10.

It′s clear that with increase of the incident wavelength and decrease of inter-elements distance, the coupling coefficient increases and the coupling length decreases, it mean that the fiber core coupling strength improve gradually. Because the increase of the fiber core spacing leads to the effective overlap area of fiber core mode reduc, it results in reduction



(a) Relation of coupling coefficient versus d



(b) Relation of coupling length versus d

Fig.10 Relation of coupling coefficient and coupling length versus wavelength and separation distance of fiber core

in coupling efficiency.

From Fig.11, we can see that when wavelength λ=1.55, the supermodel intensity of output light for arrangement Fig.9(b) is more stable than Fig.9(a), so this structure is more suitable for scanning system.

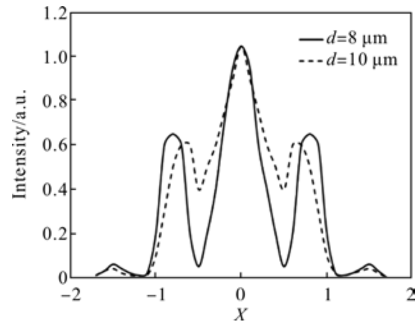


Fig.11 Intensity of output for different arrangements

4 Conclusion

Based on wave-guide OPA theory, we design a new OPA system based-on wave-guide, optical fiber is used as light transmission, $LiNbO_3$ wave-guide is used phase modulator, then we propose a new design to use the PCF as the output array.We analyze the electrooptical effect of $LiNbO_3$ wave-guide, wave-guide OPA theory and grating diffraction theory, then through the simulation experiments, the feasibility of the system is tested. Later we focus on the influence of the parameter of PCF array structure on the output diffraction characteristics.

Experimental results show that as for PCF array, the quantity of fiber core, the inter-elements distance and the parameter of structure can affect the FWHM, output intensity and normalized amplitude. Compared with traditional fiber array, PCF array is more suitable for its small spacing and better transmission characteristics and dispersion characteristics. With further development of PCF, the system will be used for laser radar or laser communication etc.

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