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A Reflection Filter of Fiber Grating With Optical High Isolation

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Abstract: In this study, a theoretical model of reflective filter with fiber grating is analyzed. The model composed of sampling fiber grating and fiber directional coupler has the function of multi-wavelengths chosen and optical isolation. The mathematical formulation of the relationship between the lights input and output is educed from the method of transformation matrix. The parameters and rules that decide spectra characteristic of the filter output and the function of optical isolation are discussed in detail and emulated. The structure parameters of this model that realize pectination filtering and optical isolation simultaneously are given. This conclusion can provide reference value for later manufacturing of this devices and solution to key technology.

Key words: Sampling grating, comb-filter, fiber directional coupler, reflection spectra

INTRODUCTION

With the rapid development of the technology of the fiber grating, a variety of active and passive components containing fiber grating come out constantly. For example, linear fiber laser[1], choosing frequency and turning device of fiber ring laser[2] and fiber grating Fabry-Perot[3] and so on. This kind of reflection filter with high isolation and narrow bandwidth which has the function of multi-wavelengths chosen proposed in this paper is one of the typical applications[4]. It is composed of fiber grating and fiber directional coupler. This filter is superior to choosing out several wavelengths we need and has natural compatibility with the fiber system. Simultaneously, it can choose out multi-routes of light-spectra with narrow bandwidth from the input light source with wide light-spectra. Moreover, it also has the advantages of constant channel spacing, high return wave isolation, high optical splitting efficiency, low additional loss and so on.

THEORETICAL ANALYSIS

Deduction of the reflection rate function of the fiber grating comb-filter: Firstly, the structure model of sampling grating is given in Fig. 1. Suppose every sampling periodic unit has complete same characteristic[5].

Next, by the method of transformation matrix, the reflection rate function of the fiber grating comb-filter is deduced roughly.

In the point of z = 0, suppose incident light is A_0, reflex light is B_0. After the first periodic unit, output lights turn into A_1, B_1. The relationship between A_1, B_1 and A_0, B_0 can be shown by this matrix:

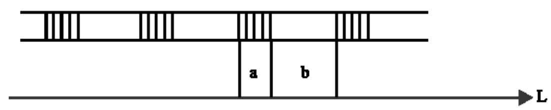

Fig. 1: Structure model of sampling grating

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = S \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \quad (1)$$

According to the same theory, owning to the uniform characteristic of every periodic unit of the sampling grating, after N periods, that is, after going through the whole sampling grating, the complex amplitude of the light beam can be shown as:

$$\begin{bmatrix} A_N \\ B_N \end{bmatrix} = S^N \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \text{ so } \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = \left(S^{-1}\right)^N \begin{bmatrix} A_N \\ B_N \end{bmatrix} \quad (2)$$

Suppose that reflection rate of sampling grating is r_g, reflection rate of light power is R_g, so,

$$R_g = |r_g|^2 = |B_0/A_0|^2 \quad (3)$$

Therefore, Rg can be obtained as long as $(S^{-1})^N$ is gained. Based on the theory of coupling model and the matrix of phase-delay, S can be deduced as:

$$S = \begin{bmatrix} S_{11}\ S_{12} \\ S_{21}\ S_{22} \end{bmatrix} = \begin{bmatrix} \left[\cosh(sa) - (j\Delta\beta/2s)\sinh(sa)\right]e^{-j\beta b} \\ \left[-(jk/s)\sinh(sa)\right]e^{-j\beta b} \\ (jk/s)\sinh(sa)e^{j\beta b} \\ \left[\cosh(sa) + (j\Delta\beta/2s)\sinh(sa)\right]e^{j\beta b} \end{bmatrix} \quad (4)$$

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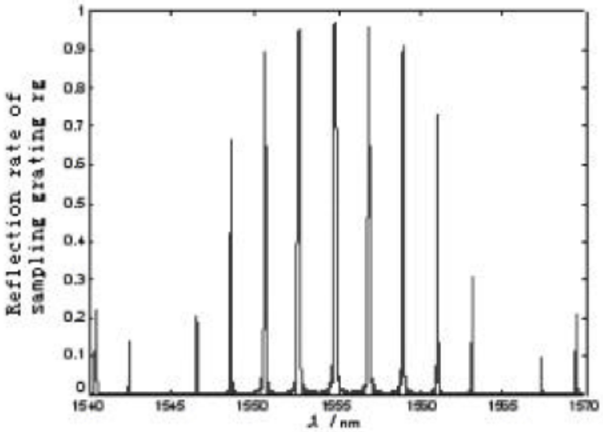

Fig. 2: Reflection spectra of sampling grating

Where, $s = (h*h-(\Delta\beta/2)^2)^{1/2}$, $h = \pi v\Delta n/\lambda$, $\beta=2\beta-2\pi/\lambda+4\pi\Delta n/\lambda$. And v-refraction rate modulation degree, Δn-average change of refraction rate, λ-wavelength of sampling grating, a-sampling length of sampling grating, b-length of non-exposal area, β-transmission constant, k-coupling coefficient of grating.

According to S, $(S^{-1})^N$ can be gained. Moreover, R is also gained, as follows:

$$R_g = |r_g|^2 = |B_0/A_0|^2 = |S_{21}|^2 / \left(|S_{21}|^2 + (\sin\Lambda/\sin N\Lambda)^2\right) \quad (5)$$

Where, is satisfied with $\Lambda=\cos^{-1}[(S_{11}+S_{22})/2]$ and N is positive integer.

The reflection spectra is emulated by Matlab as shown in Fig. 2. Those concerned parameters are given out: λ = 1.555 μm, $\Delta n = 5.0\times1.0^{-4}$, v = 1.0, N = 30, T (sampling period) = a+b = 400 μm, fill ratio is b/(a+b) = 0.3.

Figure 2 shows us clearly that passing through the reflection of the sampling grating, a light source with wide spectra can form a series of light-waves with narrow spectra and constant channel spacing.

Structure model of optical filter: The theoretical model of fiber grating reflection filter with high isolation and narrow bandwidth which has the function of multi-wavelengths chosen is given in Fig. 3.

FBG_3, FBG_4 both are sampling gratings shown in Fig. 1. Suppose the reflection rate of sampling grating in the third arm is Rg_3, the fourth is Rg_4. Suppose the fiber directional coupler is composed of the single-mode fiber, then, the guided mode transmitted in every arm of the fiber directional coupler only has the basic mode which transmits in the positive and negative directions. E_1^{in} is used to represent light field input from port 1 of the coupler, E_i^{out} (I = 1,2) represents light field output from port, α represents coupling coefficient of fiber

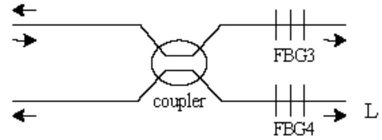

Fig. 3: Optical filter model

directional coupler and ñ is fiber loss, all of them have nothing to do with the wavelength and polarization.

Neglect insert loss of the directional coupler and because ñ is very little, it also can be neglected. Suppose $r_3 = r_{g3}\exp(-2j\beta l_3)$, $r_4 = r_{g4}\exp(-2j\beta l_4)$, β-represents transmission constant, l_i represents fiber length between the center of fiber directional coupler and FBG_3, FBG_4. Suppose FBG_3 has the same structure parameters with FBG_4. According to the transformation matrix of light amplitude of fiber directional coupler, this equation comes into existence:

$$\begin{bmatrix} E_1^{out} \\ E_2^{out} \end{bmatrix} = \begin{bmatrix} (1-\alpha)^{1/2} & j\alpha^{1/2} \\ j\alpha^{1/2} & (1-\alpha)^{1/2} \end{bmatrix} \begin{bmatrix} r_3 & 0 \\ 0 & r_4 \end{bmatrix} \begin{bmatrix} (1-\alpha)^{1/2} & j\alpha^{1/2} \\ j\alpha^{1/2} & (1-\alpha)^{1/2} \end{bmatrix} \begin{bmatrix} E_1^{in} \\ 0 \end{bmatrix} \quad (6)$$

After a series of calculation, the formulation of output light from port 1, 2 of the coupler is obtained as:

$$\begin{cases} E_1^{out} = \left[(1-\alpha)r_3 - \alpha r_4\right] E_1^{in} \\ E_2^{out} = \left\{ j\left[(1-\alpha)\alpha\right]^{1/2} (r_3 + r_4) \right\} E_1^{in} \end{cases} \quad (7)$$

According to the formulation of light field $I=E^*E=|E|^2$, output light power from every port can be obtained as:

$$\begin{cases} I_1^{out} = \left(\alpha^2|r_4|^2 + (1-\alpha)^2|r_3|^2 - 2\alpha(1-\alpha)|r_3|\cdot|r_4|\cos(\Delta\Phi)\right) |E_1^{in}|^2 \\ I_2^{out} = \alpha(1-\alpha)\left|(r_3 + r_4)E_1^{in}\right|^2 \\ \Delta\Phi = 2\beta(l_3 - l_4) \end{cases} \quad (8)$$

Next, the working theory of the filter with high isolation and narrow bandwidth will be introduced (Fig. 3).

Suppose input light field from port is $E_1^{in}(\lambda_i)$ (λ_0, λ_1, λ_2, ..., λ_n). After being coupled, it turns into two routes which, respectively reach FBG_3, FBG_4. Those light-waves out of the range of the reflection spectra of the sampling grating can't be reflected by FBG_3 and FBG_4. They are output directly from port 3 and 4. Those light-waves within the range of the reflection spectra reflected by FBG_3 and FBG_4 become a series of ones with narrow spectra and constant channel spacing, which pass through fiber directional coupler again and are output, respectively from port 1 and 2.

Two beams of light reflected back by FBG_3 and FBG_4 are coherent lights and they will interfere with each other after meeting in the coupling area of fiber coupler. Try to choose properly the coupling parameters of fiber coupler and the fiber length from the center of fiber directional coupler to FBG_3, FBG_4 and the structure parameters of FBG_3, FBG_4 and make sure they are same as possible as they can so that the result of the interference with two beams of light is that output light power from port 1 of fiber coupler is zero and output light power from port 2 reaches its peak point. Because output light power from port 1 of fiber coupler is zero, this component's access doesn't produce reflection lights, thus it doesn't bring interference to the light source and the whole system, which can avoid producing error codes and instability of the system brought by reflection light interference. And output light intensity from port 2 of fiber coupler is a series of narrow spectra with constant channel spacing and different output wavelengths (Fig. 2).

DISCUSSION

An optical filter with infinite return wave isolation and high optical splitting efficiency has much more practical value. The relationship between return wave isolation, optical splitting efficiency and model structure parameters will be discussed in detail in following paragraphs. Based on these discussions, a conclusion is given to provide the conditions which assure the optical filter shown in Fig. 1 can not only choose out several wavelengths we need, but has high return wave isolation and optical splitting efficiency at the same time. The parameters of sampling grating are same as before: λ (wavelength of fiber grating) = 1.555 μm, λ_0 (peak wavelength of input light) = λ = 1.555 μm, the range of wavelength from 1.540 to 1.570 μm.

Return Wave Isolation: According to formula[6-8], we can see that port 1 of the model is both the import of E_1^{in} and the export of E_1^{out}. In the fiber digital communication system and fiber sensor system, if the entrance of light field can input light field and output light field at the same time, it'll generate to optical interference phenomenon which may cause input signals to distort, more seriously, it'll bring error codes and instability of the system. So, the deeper the return wave isolation is, the stronger the restraint to the interference will be and the better the capability of the components will be.

Give the formulation of the return wave isolation:

$$R_L = 10\lg\left[\left|E_1^{in}(\lambda)\right|^2 \Big/ \left|E_1^{out}(\lambda)\right|^2\right] \quad (9)$$

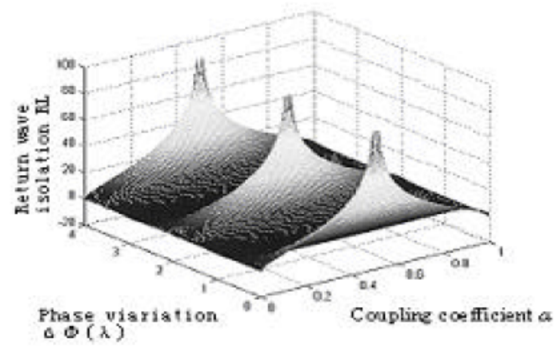

Fig. 4: Relationship between Return Wave Isolation R_l and Coupling Coefficient α and Phase Variation $\Delta\Phi(\lambda)$

The relationship between the return wave isolation R_l and coupling coefficient α, phase variation $\Delta\Phi(\lambda)$ is shown in Fig. 4, where, the reflection rate of light power of grating $|r_3(\lambda)| = |r_4(\lambda)| = 0.99$.

From Fig. 4, we can see clearly that the requirements which make return wave isolation infinity are:

α(coupling coefficient of the coupler) = ½, $\alpha^{1/2}|r_3(\lambda)| = (1-\alpha)^{1/2}|r_4(\lambda)|$. $\Delta\Phi(\lambda)$ (phase variation of two arms) = 2 mπ (m = 0, ±1, ±2,....).

If those requirements can't be satisfied with, the return wave isolation will drop. This relationship is as (Fig. 4).

Optical splitting efficiency: Optical splitting efficiency refers to the proportion of the working wavelengths we need to choose out in output wavelengths which are light source with wide-band pass through filter and then output from port 2. It reflects the optical splitting degree of working wavelengths that components need. The higher the degree is, the lower the insert loss and additional loss of working wavelengths will be.

Give the formulation of the optical splitting efficiency η:

$$\eta = \left|E_2^{out}(\lambda)\right|^2 \Big/ \left|E_1^{in}(\lambda)\right|^2 \quad (10)$$

The relationship between η, α and $\Delta\Phi(\lambda)$ is shown in Fig. 5, where, $|r_3(\lambda)| = |r_4(\lambda)| = 0.99$.

We can see that when (I) α = ½, (ii) $\Delta\Phi(\lambda) = 2m\pi$ (m = 0, ±1, ±2,....).come into existence at the same time, η reaches its peak value, otherwise, output light power from port 2 will decrease obviously.

The relationship between the optical splitting efficiency η and the reflection rate of sampling grating R is shown in Fig. 6. Where, α = ½, $\Delta\Phi(\lambda) = 2m\pi$ (m = 0, ±1, ±2, ...). The reflection rate of the grating R influents on the optical splitting efficiency directly and the η will increase if R increases.

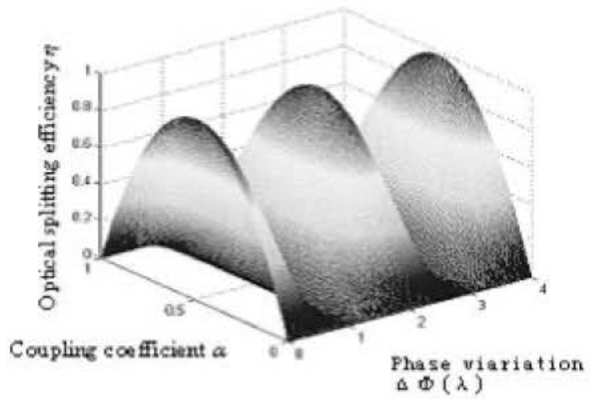

Fig. 5: Relationship between optical splitting efficiency η and coupling coefficient α and phase variation $\Delta\Phi(\lambda)$

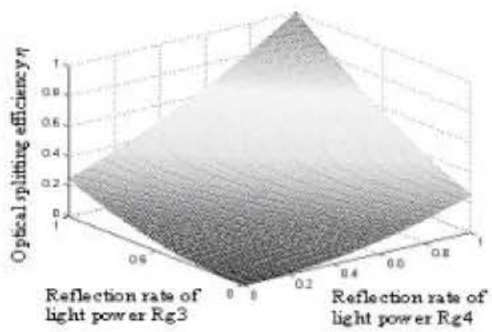

Fig. 6: Relationship between optical splitting efficiency η and the reflection rate of light power

Figure 7 shows the relationship between the optical splitting efficiency η and the wavelength λ. We can see that when (I) $\alpha = ½$, (ii) FBG3 has the same structure parameters with FBG4 and they both have high reflection rates, furthermore, the phases of the two arms must match with each other. If so, output light power from port 2 is a series of light-waves of different wavelengths with narrow spectra and constant channel spacing and the spectra of output light with full width and half maximum $\Delta\lambda_{1/2}$ is about 0.2 nm, so the effect of pectination filtering is remarkable.

According to above analysis, we can draw the conditions that assure the fiber grating comb-filter as Fig.1 shows finishes the basic requirement of choosing out working wavelengths we need and has high return wave isolation and optical splitting efficiency simultaneously:

- $\alpha = ½, \Delta\Phi(\lambda_0) = 2m\pi, (m = 0, \pm1, \pm2, \ldots)$

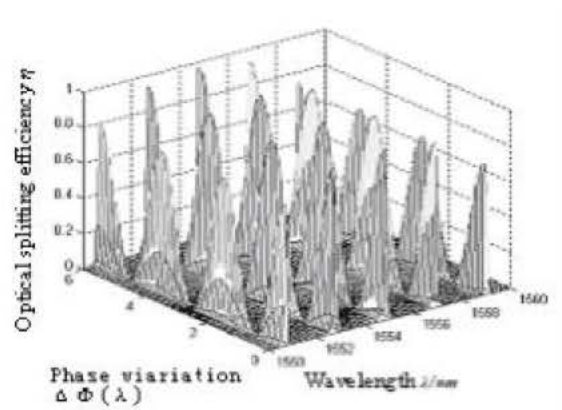

Fig. 7: Relationship between optical splitting efficiency η and the wavelength of reflection light of sampling grating

- The reflection rate of the sampling grating must be as higher as possible and the equation $|r_{g3}(\lambda_0)| = |r_{g4}(\lambda_0)|$ must be assured as possible as it can.

CONCLUSIONS

The theoretical model of reflection filter with fiber grating is proposed in this paper. This model of all-optical fiber with high isolation and narrow bandwidth has better compatibility with the fiber system. It not only can realize multi-wavelengths chosen, but has the function of optical isolation. Through connecting serieses of them together and properly changing some structure parameters, it can realize add/drop voice channel in the system of optical communications. Futher more, this model can be used to make up a variety of fiber passive components such as all-optical fiber WDM device. Therefore, this model as an optical transmission component can be used in DWDM system widely. It not only can be used in the input interface in front of the optical receiver, but can be used in the output interface of light source.

This kind of the filter is all-optical fiber without any optical division components[6]. It can be more compatible with the fiber system than the traditional optical filter. General fiber grating filter usually uses its band-rejection characteristic to realize the function of filtering[7]. It hasn't the function of high isolation.

After analyzing the relationship between the model characteristic of this filter and its structure parameters[8], we obtain the theoretical parameters which have the function of pectination filtering and optical isolation at the same time. Simultaneously, we reach the realizable conditions. This conclusion can provide reference value for later manufacturing of this device and solution to key technology.

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