研 究 速 報

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An Optical Modulator Using Kerr Effect in Optical Fiber Directional Coupler

ケル効果による光ファイバ方向性結合器形光変調器

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A new optical modulator in an optical fiber directional coupler, where the coupling of two optical fibers is electrically controlled by Kerr effect, is proposed and experimentally verified. This modulator consists of two parallel fiber cores immersed in a Kerr-effect liquid. The characteristic of this modulator is theoretically analyzed and it is shown that a change of the refractive index by Kerr effect in the liquid in the order of 10^{-4} is sufficient to a complete switching for the coupling length of 5 mm.

Introduction

In future optical fiber communication systems, the optical switch and directional coupler by using the optical fiber itself will play an important role. The integrated optical circuit [1~3] can not be used directly with fibers. Particularly, in the case of the single mode fiber, it is very difficult to couple these devices to the fiber.

Several types of mechanical fiber switches have been reported, tn which the optical path is switched by rotating the mirror or by moving the fiber itself [4]. Their switching speeds are limited by the slow response of the mechanical actions.

In this paper an optical modulator, or optical switch, where the coupling of two single mode fibers is electrically controlled by Kerr effect, is proposed and it is shown that a complete switching can be obtained by changing the refractive index of the surrounding liquid in the order of 10^{-4}. The modulation degree was measured using ethyl cyanoacetate as the Kerr effect liquid.

Theory

The geometry of the fiber coupler is shown in Fig. 1. Fiber cores of the refractive index N_1 and the radius A are put in parallel by the length L, and the surrounding of the cores is filled with a liquid whose refractive index is N_2. The fibers guide the fundamental mode HE_{11} only.

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When the input power of fiber 1 is I_0, the coupled power from fiber 1 to fiber 2 is given by

$$I_2 = I_0 \sin^2 CL \qquad (1)$$

where C is the coupling coefficient of HE_{11} mode.

If a Kerr effect liquid is used as the surrounding medium of the cores and the fiber coupler is inserted between a pair of electrodes (Fig. 2), the coupling coefficient is changed by the applied electric field, and the coupled power is changed

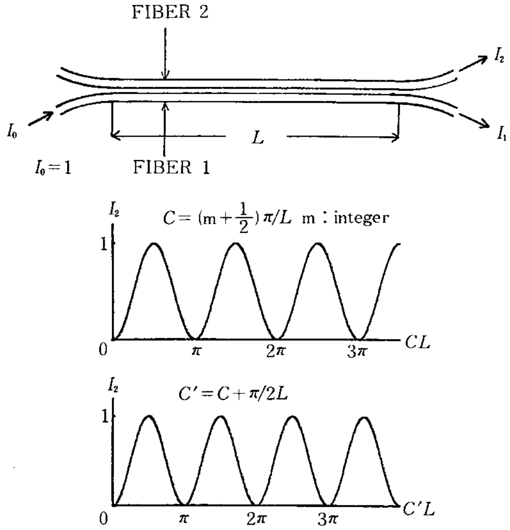

Fig. 1 Optical fiber directional coupler and coupled power

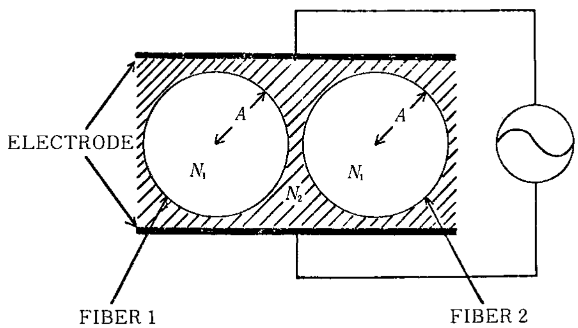

Fig. 2 Optical modulator configuration

according to eq. (1). The input power in fiber 1 is transfered to fiber 2 when C is an odd multiple of $\pi/2L$, while it appears in fiber 1 when C is even multiple of $\pi/2L$. In this way, an optical modulator, or switch, can be constructed.

Under the assumption of weakly guiding, the coupling coefficient of HE_{11} mode C can be written as [5]

$$C=\frac{\sqrt{\delta}U^2}{AV^3}\frac{K_0(Wd/A)}{[K_1(W)]^2} \qquad (2)$$

where V is the normalized frequency, U and W are the normalized transverse propagation constant in the core and in its surrounding, respectively, d is the distance between the two core centers, and $\delta=1-(N_2/N_1)^2$. The normalized frequency V is given by

$$V=kA\sqrt{N_1^2-N_2^2} \qquad (3)$$

where k is the wavenumber of light in vacuum, and U and W are related to V by the relation

$$U^2+W^2=V^2 \qquad (4)$$

To obtain the values of U and W, we must solve the eigenvalue equation [6]

$$\frac{UJ_1(U)}{J_0(U)}=\frac{WK_1(W)}{K_0(W)} \qquad (5)$$

together with eq. (4).

Fig. 3 shows the coupling coefficient versus the refractive index difference between the core and its surrounding, where A is 2 μm, N_1 is 1.458, and the separation between two fiber cores is 1 μm. It is shown that the coupling coefficient has the maximum value when the index difference is about 2. The corresponding coupling efficiency I_2/I_0 for $L=5$ mm is shown in Fig. 4. From this figure, in order to perform a complete switching the refractive index change of 2×10^{-4} is required.

Experimental Results

The modulation degree as a function of the applied voltage was measured with the experimental set-up shown in Fig. 5. The fibers used have the following parameters: $A=2\,\mu$m, $N_1=1.458$, and cladding diameter is 100 μm. The claddings of the fibers are etched off to the cores of 4 μm diameter by hydrofluoric acid. Fig. 6 shows the configuration of the coupling region. In Fig. 7, typical Kerr effect liquids are listed are listed. Since the refractive index of nitrobenzene or nitrotoluene, which has a large Kerr constant, is larger than that of the silica core, ethyl cyanoacetate was used as the Kerr effect liquid, of which the refractive index is 1.4179 and Kerr constant is 4.31×10^{-13} m/V^2. The gap between the electrodes is 1 mm.

Fig. 8. shows the modulation degree versus the applied voltage; the solid line shows the calculated modulation degree when the separation of the fibers is 1.3 μm, and cross (x) denotes the measured value. The resulted modulation degree was 10^{-4} and this agrees wtih the theoretical value.

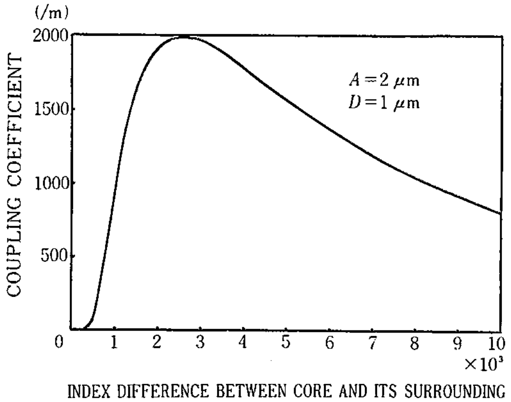

Fig. 3 Coupling coefficient of HE_{11} mode vs refractive index difference between core and its surrounding

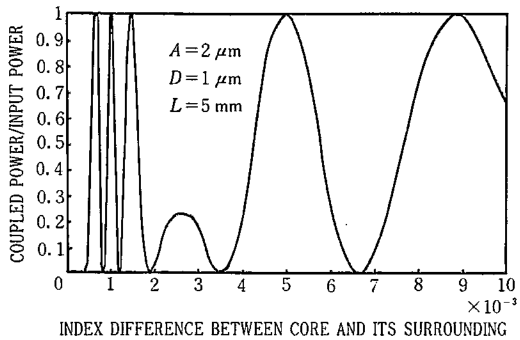

Fig. 4 Coupled power vs refractive index difference between core and its surrounding

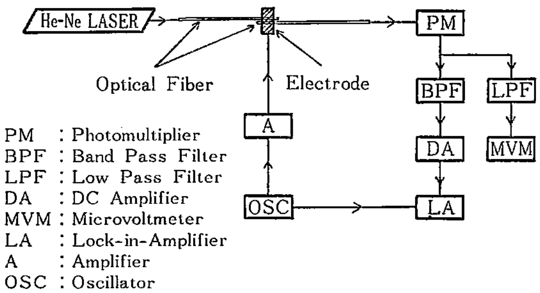

Fig. 5 Schematic diagram of the experimental set-up

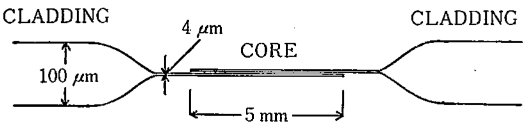

Fig. 6 Configuration of fiber coupler in coupling region

Liquid	Symbol	Kerr constant K, 10^{-7}esu (λ=0.589 μm)	Static dielectric constant ε	n_D^{20}/Hβ-Hα
Carbon dissulfide	CS_2	+3.23	2.6	1.6295/0.0343
Acetone	C_7H_6O	+16.3	21.9	1.3591/0.0068
Methyl ethyl ketone	C_4H_8O	+13.6	18.5	1.3791/0.0071
Pyridine	C_5H_5N	+20.4	12.5	1.509/0.0163
Ethyl cyanoacetate	$C_5H_7NO_2$	+38.8	27.7	1.4179/0.0044
o-Dichlorobenzene	$C_6H_4Cl_2$	+42.6	7.5	1.549/0.0176
Benzenesulfonyl chloride	$C_6H_5ClO_2S$	+89.9	....	....
Nitrobenzene	$C_6H_5NO_2$	+326	36.1	1.5529/0.0252
Ethyl B-aminocrotonate	$C_6H_{11}NO_2$	+31.0	....	....
Paraldehyde	$C_6H_{12}O_3$	-23.0	14.5	1.4198/0.0081
			12.0	
Benzaldehyde	C_7H_6O	+80.8	18.0	1.5464/0.0232
			14.1	
p-Chlorotoluene	C_7H_7Cl	+23.0	6.4	1.521/0.0164
o-Nitrotoluene	$C_7H_7NO_2$	+174	27.4	1.5462/
m-Nitrotoluene	$C_7H_7NO_2$	+177	23.8	1.5475/
p-Nitrotoluene	$C_7H_7NO_2$	+222	18.7	1.5346/
Benzyl alcohol	C_7H_8O	-15.4	13.0	1.5399/0.0173
			10.8	
m-Cresol	C_7H_8O	+21.2	13.0	1.540/0.0181
			5.0	
m-Chloroacetophenone	C_8H_7ClO	+69.1		
Acetophenone	C_8H_8O	+66.6	18.3	1.5339/0.0217
			15.8	
Quinoline	C_9H_7N	+15.0	9.0	1.6283/0.0312
Ethyl salicylate	$C_9H_{10}O_3$	+19.6	8.6	1.5226/0.0206
Carvone	$C_{10}H_{14}O$	+23.6	11.2	....
Fthyl benzoylacetate	$C_{11}H_{12}O_3$	+16.0	12.8	1.5338/0.0202
Water	H_2O	+4.0	81	1.3330/

Fig. 7 Typical Kerr effect liquids

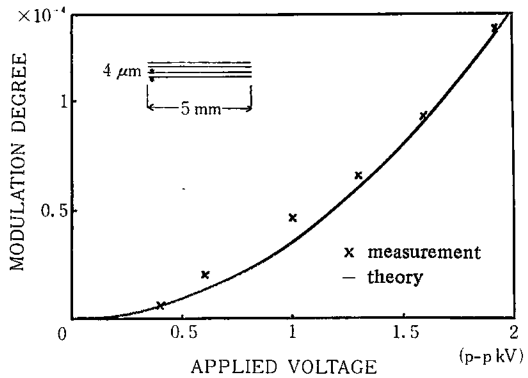

Fig. 8 Modulation degree vs applied voltage

Since the Kerr constant of the liquid is ten times smaller than nitrobenzene and the index difference between the cores and the liquid is large, the modulation degree was very small. The coupling efficiency without the applied voltage is measured to be 0.2%, while its calculated value is 1%, This would be caused by the radiation loss by the surface roughness in the etched region and the mode conversion loss at the input transition.

Conclusions

An optical modulator in the optical fiber coupler is proposed and experimentally verified. The measured modulation degree was very small because of the large index difference between the cores and the liquid and the small Kerr constant of the liquid. A better performance would be obtained if a core glass and a liquid of large Kerr constant were chosen so that their index difference should be small enough. For example, if nitrobenzene (n=1.55) and core (n=1.549) are used for the coupler with the electrode gap 100 μm and with applied voltage 1000 V, 100% modulation can be achieved. In this case, the temperature must be kept within 10^{-2} degrees.

The development of the fiber etching technique will make it possible to use this fiber coupler modulator as a modulating branch or optical switch.

Acknowlegements

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正　誤　表（12月号）

頁	段	行	種別	正	誤
752	左	↑6	数式	$\frac{\partial x_{k_0}}{\partial n}$	$\frac{\partial x_k}{\partial n}$
〃	右	↓1	〃	〃	〃
〃	〃	〃	〃	$\frac{\partial z_0}{\partial n}$	$\frac{\partial z}{\partial n}$
〃	〃	↓5	〃	x_{5_0}	x_5
〃	〃	↓6	〃	$\partial x_{k_0}/\partial n$	$\partial x_k/\partial n$
753	〃	↓4	〃	$\overline{\varphi_j}$	φ_j
〃	〃	↓5	〃	$_j\overline{H}_m^{s\pm}$	$_jH_m^{s\pm}$
〃	〃	↓18	〃	$-m_s<m\leqq m_s$	$-m_s<m<m_s$
754	左	↑17	〃	$_j\overline{H}_{m'}^{s-}$	$_jH_{m'}^{s-}$
〃	右	↑14	〃	$\|x-x'\|$	$x-x'$
758	右	↓5	〃	2	3
	〃	↑1	参考文献	Vol. 18 No. 201	Vol. No. 201
762	〃	↓12	数式	$(\alpha_n+\Delta\alpha_c)^2$	$(\alpha_n+\alpha_c)^2$
782	左	↓4	総索引	江澤良孝	江澤良平
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