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NOTES

Response Time of Plastic Optical Fiber doped with Organic Fluorescent Material

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Gas-insulated systems (GIS) are reliable for power equipment because they can be sealed with highly insulating compounds like six-fluorinated sulphide (SF_6) gas. As a results, GIS is widely used for electrical substation switching. However, as inner structures are complex and metal sealed at about 5 kg cm^{-2}, it requires a long time to return to a normal state after an accident has occurred. Therefore, it is important to anticipate accidents, especially gas discharge. To detect partial gas discharge, several sensors have been developed such as extraordinary electrical field, vibration, and sound detectors.[1,2] However, these sensing technologies cannot accurately detect the gas discharge locations. For these reasons, it is desirable to have an optical sensor which dose not affect electromagnetic interference (EMI).

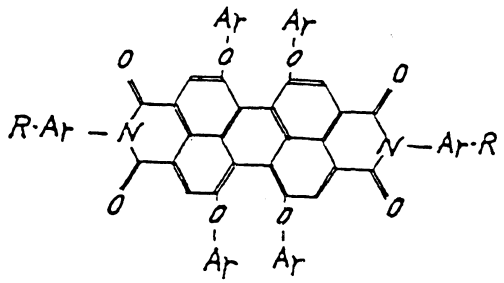
Plastic optical fiber (POF) has been used widely for short-distance communication applications such as local area networks (LANs),[3] datalinks, and multinode bus networks.[4] Recent POF popularity can be attributed to its easy processing and large diameter, which enable highly efficient fiber coupling and beam insertion. POF have been developed usage fluorescent dopants such as perylene and other organic material[5] which converts shorter than wavelength fluorescence incident light to fluorescent light. This fiber is expected to detect discharge light and discharge location in optically sealed device (such as GIS) and the position of discharge to measure the terminal output power of both.[6] The SF_6 gas discharge duration was reported to be in 20 ns.[7] However, the fiber fluorescence response time corresponding to sensor efficiency has not yet been measured in detail. This paper describes the response times of POF doped with perylene dye, 2,5-bis[5-*tert*-butyl-2-benzoxazolyl] thiophene (BBOT), and the mixtures of two or three dyes for fluorescence measured by a N_2 laser with a wavelength of 337 nm and a pulse width of 4 ns. We studied these response times for partial SF_6 gas discharge sensors.[7]

EXPERIMENTAL

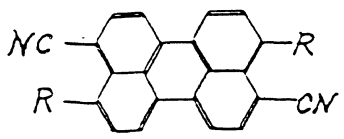
POF consists of a polycarbonate (PC) core with a refractive index of 1.586, and a cladding of blended poly(methyl methacrylate) (PMMA) and poly(vinylidene fluoride) (PVDF) with a refractive index of 1.445.[5] The PC core is doped with fluorescent materials, perylene dye (Figure 1), BBOT, and the mixtures of two or three dyes, at concentrations of 0.01 wt% to 0.1 wt%. The fluorescent color are blue for BBOT, green for perylene, and red for perylene and mixtures (Table I). POF was spun into a filament by forcing the molten PC and the PMMA and PVDF polymer blend

Table I. Optical characterisities of fluorescent fiber

Material	Fluorescent wavelength	Halfwidth	Pomping (τ_p) + internal conversion time, τ_e	Fluorescent life time, τ_f	Response time
	nm	nm	ns	ns	ns
BBOT	470	70	3.2	1.6	10
Perylene (Green)	565	54	5.5	6.7	22
Perylene (Red)	655	48	6.4	8.4	26
Green + Red	670	55	8.2	10.1	32
BBOT + Green + Red	660	60	11.2	10.1	36

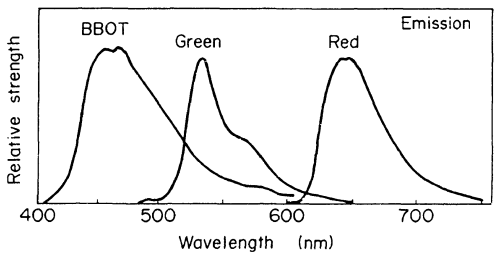


(a) Red

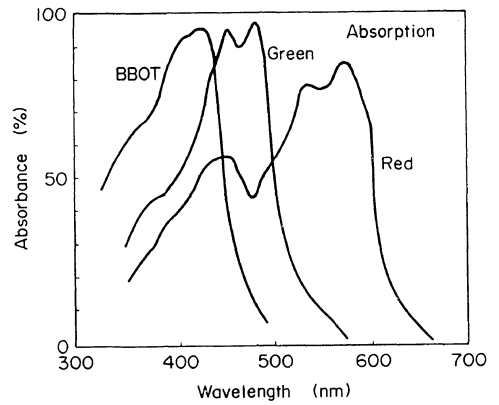


(b) Green

Figure 1. Perylene dye chemical structure.



(a) Absorption



(b) Emission

Figure 2. Fluorescent fiber absorbed and emitted spectrum.

through double nozzles kept near the melting point. By controlling drive velocity, the fiber diameter was maintained at 1 mm.[8] The absorbed and emitted spectrum from the fiber end was measured by focusing a xenon lamp through the appropriate color filter set parallel along the fiber. Spectroscope measurement results are shown in Figure 2. Fluorescence response time was determined from fluorescence excitation dependence using an N_2 laser with a wavelength of 337 nm and a pulse width of 4 ns. The incident laser radiated perpendicularly to the fiber. The distance between the incident laser and the fiber end was 3 cm (Figure 3). The fiber optical delay time is 0.15 ns. The excited fluorescence from

Table II. Conversion efficiency η and attenuation loss α for fluorescent fibers[7,a]

Light source wavelength	520 nm		471 nm		406 nm	
Fluorescence	η/%	α/dB m^{-1}	η/%	α/dB m^{-1}	η/%	α/dB m^{-1}
Perylene (Red)	0.21	2.6	0.0010	3.6	0.00032	3.3
Perylene (Green)	(not observed)		0.0050	4.5	0.00040	4.7
BBOT	(not observed)		(not observed)		0.0035	9.2

[a] η and α are calculated by $I=\eta I_0 \exp(-\alpha L)$, where I is the optical output power, I_0 is the incident light source around the fiber, and L is the distance from the end of the fiber to the incident light source. η can be calculated from the measured value I/I_0 when $L=0$.

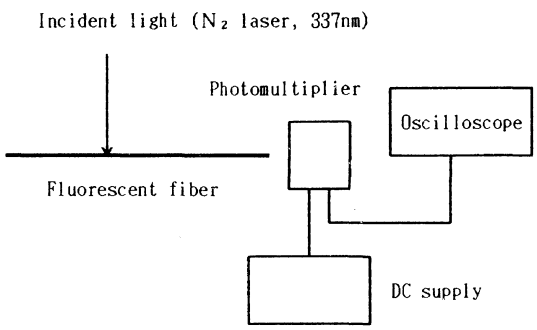


Figure 3. Measured response time for fluorescent fiber.

fiber end was detected by a photomultiplier and time dependence observed on an oscilloscope.

The fiber conversion efficiencies and attenuation losses are shown in Table II.[7]

RESULTS AND DISCUSSION

Principle of Fluorescence

Figure 4(a) shows fluorescence effects for the fiber doped with one type of dye. When light rays with wavelength λ_1 are incident to the fiber core, the dye absorbs the rays, isotropically emitting monochromatic fluorescent rays in the core which are a longer wavelength of λ_2. These rays are reflected at the core and cladding interface when the incident angle, θ, exceeds the critical angle, θ_c $\{\theta_c=\sin^{-1}(n_2/n_1)$, where n_1 is the core's refractive index and n_2 is the cladding's refractive index$\}$. The reflected rays are transmitted along the fiber axis and output at the fiber ends.

Figure 4(b) shows fluorescence effects for the fiber doped with two kinds of dyes (A and B). The emitted wavelength differs in each case: λ_A and λ_B. λ_A is shorter than λ_B. The emitted fluorescent rays of λ_B are transmitted along the fiber axis as λ_2. The emitted fluorescent rays of dye A immediately reabsorbed into dye B and the emitted wavelength becomes λ_B. The wavelength at the fiber ends is only $\lambda_B=\lambda_2$. In Table I, the fiber's fluorescent wavelengths are almost same for doping with perylene red, perylene green + perylene red, and BBOT + perylene green + perylene red.

Response Time

Figure 5 shows the time dependence of the normalized fluoresence intensity at the fiber end. The time from zero to maximum intensity corresponds to the sum of the times from which electrons excit from the ground state to the excited state. That is, pumping time (τ_p) and internal conversion time, τ_c, in which this excited electron emits to the phonon and falls to the lowest energy level of the excited state. The decay time corresponds to the time required for the excited electron to fall to the ground state and emit fluorescent light. The decay intensity of fluorescence, I, is approximated by

$$I \propto n \times \exp(-\tau/\tau_f), \quad (1)$$

where n is the number of excited electron, τ is

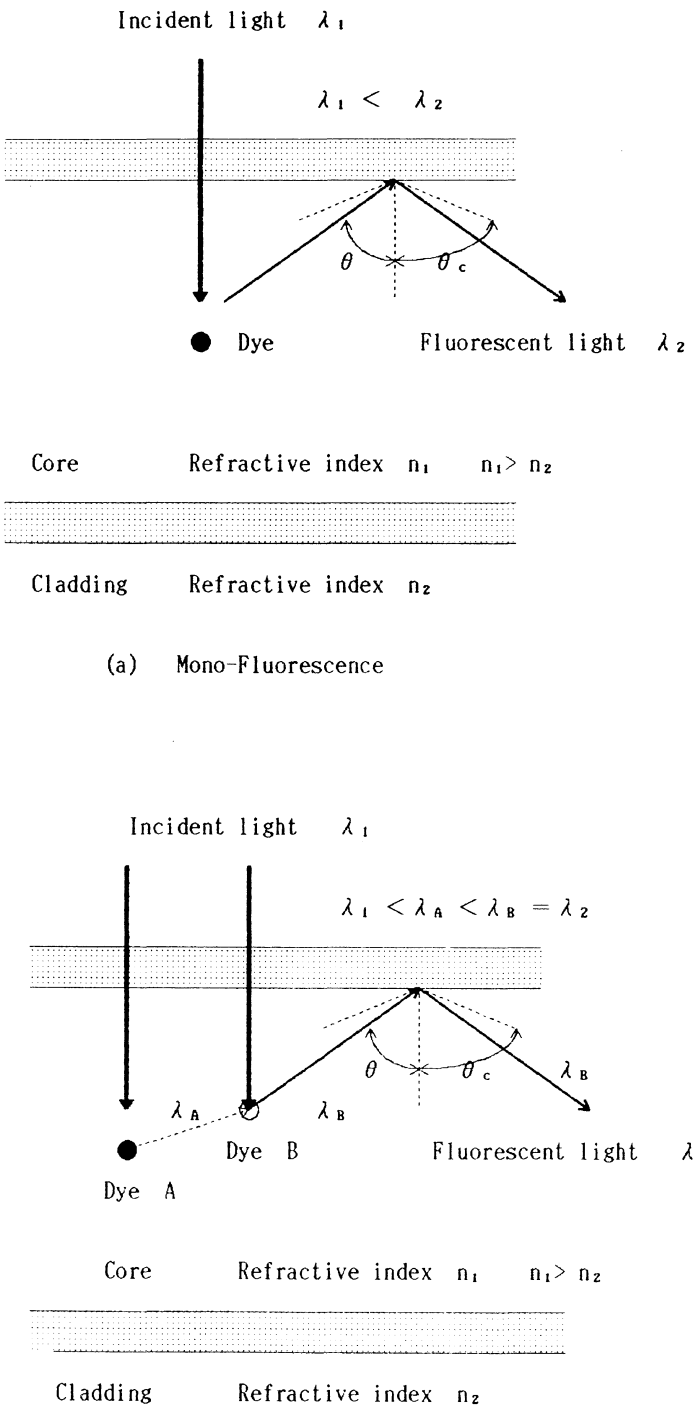


Figure 4. Optical transmission effects of fluorescent fiber: (a) mono-fluorescence; (b) double-fluorescence.

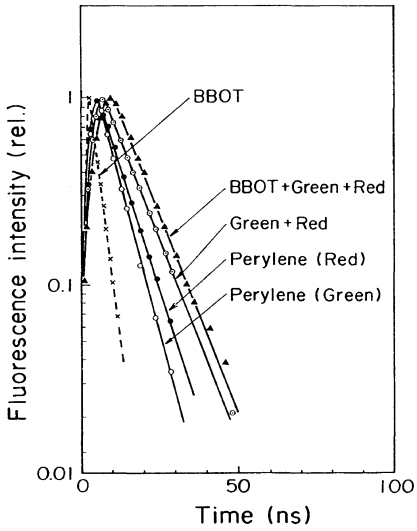


Figure 5. Fiber fluorescence intensity time dependence.

the time and τ_f is the fluorescence decay time. Based on the results of Figure 5, Table I summarizes the analysis for each parameter. $\tau_p+\tau_e$ and τ_f values increases for BBOT, perylene green, and perylene red, in this order. τ_f of perylene is almost same 6.0 ns in polar solvent.[9] The mixture's values also increased as compared to those of mono dye. The mixture's increase of $\tau_p+\tau_e$ is predictable from the mechanism process described in Figure 2(b). The dye A fluorescent material with a short wavelength emits fluorescent light after the incident light absorption. The emitted fluorescence is reabsorption in dye B with a longer wavelength. This material reemits the fluorescent light, increasing $\tau_p+\tau_e$. Table III shows the emited peak wavelength, the emission spectrum halfwidth and typical LED response time.[10] The decay to one-tenth of maximum intensity is more than 90 ns. The response time for the fluorescent fiber is below 40 ns, the fluorescent fiber responds to a 10-MHz signal with a visual wavelength. Fluorescent fiber provides a specific monochromatic light by using a light source in the ultraviolet or visible region. The fluorescent fiber's optical coupling efficiency is superior to

Table III. Visible light LED response time

LED	Peak emission Wavelength	Halfwidth	Response time
	nm	nm	ns
Red	635	40	90
Yellow	583	36	90
Green	565	28	500

that of LEDs because the fiber is easily adjusted.

CONCLUSIONS

Plastic optical fiber doped with organic fluorescent materials converts incident light to monochromatic light in less than 40 ns, and less than 26 ns for only mono-fluorescent materials such as BBOT and perylene. Connecting dye doped POF to commercial PMMA-core provides a fiber light source response to signals exceeding 10 MHz. This signal speed can not be transmitted by LEDs, and is also useful for detection of SF_6 gas discharge. Typical switch parameters could be a pulse width of about 20 ns and a peak spectrum wavelength of 500 nm. The POF absorption spectrum with a mixture of two or three kinds of fluorescent dopants is broad compared to the spectrum with only one dopant. As conversion efficiency to fluorescence is increased, POF will become increasingly useful for sensing weak light and effects such as corona discharge.

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