Sensitivity of Two Core Fiber Coupling to Light-Induced Defects

M. A. SAIFI, Y. SILBERBERG, A. M. WEINER, H. FOUCKHARDT, AND M. J. ANDREJCO

Abstract—We report on permanent changes in the refractive index of germania-doped silica core fiber nonlinear directional coupler, exposed to 620 nm wavelength high-intensity 100 fs pulses. The index change, of the order of 10^{-5}, is estimated from the detuning aspects of the coupler. We discuss both the constraints and beneficial aspects of these defects for nonlinear optical devices.

Fig. 1. Fiber nonlinear directional coupler. L_c represents one coupling length.

NONLINEAR optical effects are gaining increasing importance for all optical signal processing devices. Such devices require high-optical power density, which in addition to the desired nonlinear optical effects, could also result in other unexpected optical phenomena. For example, the limitations imposed by two photon absorption on the nonlinear directional [1] coupler switch have recently been discussed. On the other hand, a defect-induced second-order nonlinearity [2]-[5] is presumed to provide a mechanism for efficient second harmonic generation in optical fibers. This paper, for the first time, reports on the effects of light-induced defects on the characteristics of a linear and nonlinear directional coupler. In the following, we first review the operating principles of the linear and nonlinear directional coupler and then describe the observed effect of light-induced defects on the coupling and switching characteristics. We show that the defects are germania related and estimate the defect-induced refractive index change from changes in the coupling characteristics. We conclude by discussing the possible defect structure and by commenting on the relevance of our observations to several other defect-related phenomena in optical fibers.

The nonlinear directional coupler based on the intensity dependent refractive index change is a potentially important device for all-optical signal processing in ultrahigh bit rate communication networks. Since it was originally proposed by Jensen [6] for optical processing, several further applications such as a pulse compressor [7], optical transistor [8], and soliton switch [9] have been proposed. All optical switching in the femtosecond regime has been demonstrated [10] in a dual core optical fiber nonlinear directional coupler. The linear and nonlinear directional couplers (Fig. 1) are based on coherent interaction between two single-mode waveguides placed in close proximity in a common cladding. The overlap in their evanescent fields causes periodic exchange of power
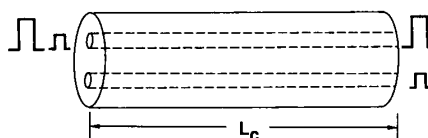
between the two waveguides. In an ideal coupler, the two guide parameters and their propagation constants are identical. In this case, the normalized output from guide 2, with input in guide 1, is given by $\mathrm{Sin}^2 \, cL$, where c is the wavelength dependent coupling coefficient and L is the coupler length. Thus, at low powers, all the light will emerge from guide 2 provided the coupler length is such that $cL = (2m - 1)\pi/2$, with m an integer. In the nonlinear regime, switching is achieved by perturbing the coupling through the intensity dependent change in the refractive index of the input core. The critical switching power [1] which detunes the coupler is given by $P_c = A\lambda/n_2L_c$, where A is the effective mode area, λ is the vacuum wavelength, n_2 is the nonlinear refractive index, and L_c is one coupling length ($m = 1$). Thus, for a typical coupler of few millimeters to few centimeters coupling length, the light-induced refractive index change for switching is given by $\delta_n = P_c n_2/A = \lambda/L_c$ and lies between 10^{-4} and 10^{-5}. Since switching is achieved via rather small index changes, it is apparent that the coupler characteristics will be sensitive to minute mismatch between the refractive indexes or propagation constants of the two guides.

In this paper, we report a small but discernible permanent change in the refractive index of a germania-doped silica glass fiber subjected to high-intensity femtosecond pulses at 620 nm. As described in an earlier publication [10], the nonlinear switching experiments were carried out with 8.6 kHz repetition rate, 100 fs (FWHM) pulses at 620 nm, and a dual-core fiber directional coupler. The coupler consisted of two single-mode germania-doped silica cores of diameter 2.8 μm, core cladding index difference 0.003, and 8.4 μm spacing between the two cores. The calculated and measured coupling length at 620 nm was about 5 mm. The typical switching characteristics of this coupler [10] have been published, from which the critical switching power is estimated to be 32 kW. The induced nonlinear refractive index change, based on an effective mode area of 15 μm^2 and nonlinear coefficients for silica 3.2 $\times$ 10^{-16} cm^2/W, is estimated to be 6.8 $\times$ 10^{-5}. As mentioned in the earlier publication [10] a gradual degradation in the coupler's low-power extinction ratio was observed during the
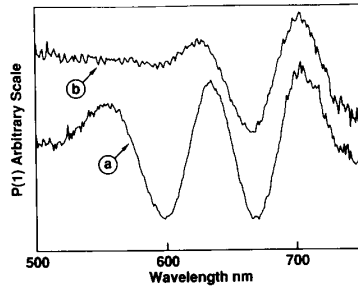
Fig. 2. Measured spectral dependence of power output from core 1 at low intensities. (a) Virgin coupler. (b) After exposure to switching pulses. Note: for clarity the curves have been displaced on the vertical axis.

Fig. 3. Calculated spectral dependence of power output from core 1. (a) Matched coupler. (b) Index mismatch 5×10^{-5}. (c) Index mismatch 1×10^{-5}.

course of the switching experiments. To check this point, the experiments were repeated with several couplers. In each case, exposure to high-intensity light caused a gradual change in the coupler characteristics. While the coupler characteristics degraded with prolonged exposure to high-intensity pulses, the evolution to the final characteristics was not uniform over the few couplers we experimented with. In some instances, we observed initial improvement in the switching behavior followed by degradation, whereas in others the degradation occurred from the start. We suspected that this effect was caused by refractive index change resulting from light-induced defects.

The effect of light-induced defects on the coupler operation can be seen from data on power transfer in the coupler as a function of wavelength. The increase in the evanescent field overlap with wavelength results in wavelength dependence of the coupling. Fig. 2(a) shows the measured wavelength dependent power transfer characteristics of an unexposed 15 mm long coupler (3 coupling length at 620 nm). This coupler, after 45 min exposure to about 120 kW peak power switching pulses, showed significant degradation in its low-power extinction ratio. Comparison of the wavelength dependent power transfer characteristics, before and after laser exposure [Fig. 2(a) and (b)], showed two major effects: first, nearly complete absence of coupling at shorter wavelengths (≤ 600 nm) accompanied by lowering of the power transfer coefficient at longer wavelengths, and second, a small shift in the power transfer extrema to shorter wavelengths.

The above suggests that the change in the coupler characteristics are due to a defect-induced index mismatch between the two guides. Furthermore, depending on the light intensity in the two guides, the index mismatch may be spatially distributed. However, as a first approximation, we assume a uniform index change which is induced in the input guide only to be constant, and we estimate the induced index difference between the two guides by fitting calculated wavelength dependent power transfer characteristics of a mismatched coupler [11], [12] to the measured values. Fig. 3(a) and (b), respectively, show the calculated power transfer characteristics of our matched coupler and a coupler with an index mismatch between the two cores of 5×10^{-5}. A comparison of Figs. 2(b) and 3(b) shows the same basic features, i.e., absence of coupling at around 600 nm, lowering of power transfer coefficient at longer wavelengths, and a shift of power
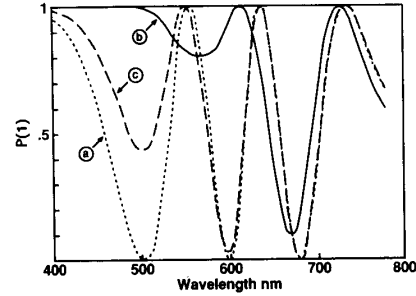
transfer extremes to shorter wavelengths. Therefore, we estimate that the defect-induced refractive index change of the input guide is roughly 5×10^{-5}. We recognize that the propagation constants of the two unexposed guides are not identical due to imperfections in fabrication such as differences in their core diameters and/or refractive indexes. Since the coupler has an order of magnitude higher sensitivity [11] to index difference than the core diameters, we consider the effect of initial index mismatch. The index difference has a much larger effect at shorter wavelengths, since in this region the overlap in the evanescent fields is rather weak. The spectral measurements show a comparatively poor contrast [Fig. 2(a)] for the first short wavelength power transfer extreme near 500 nm, from which the initial index mismatch [Fig. 3(c)] is estimated to be 1×10^{-5}, substantially less than our estimate of 5×10^{-5} for the defect-induced refractive index change. Furthermore, as can be seen (Fig. 2) for the virgin as well as the light exposed coupler, the contrast at longer wavelengths is less sensitive to index mismatch. This is because the coupler is now operating at smaller values of the normalized frequency, resulting in strong coupling, which requires a higher index mismatch to disturb it.

Experiments were also done to determine the material aspects of the light-induced defects. It is known that radiation-induced defects can be annealed out [13] by a high temperature annealing process. Based on this, the coupler was annealed at about 700°C for 8 h, which nearly restored its original power transfer characteristics. This confirms our earlier assumption that the changes in the coupler characteristics are due to refractive index changes associated with light-induced defects. Furthermore, from the radiation-induced defect studies of glasses [14] it is known that pure silica is less prone to radiation-induced defects and has higher damage threshold. Therefore, to further confirm that the observed effect was due to germania-doped silica cores, a coupler with essentially the same parameters but pure silica core and fluorosilicate cladding [15] was fabricated, and switching curves similar to those reported for germania-doped coupler were observed. As expected, even after prolonged exposure to high-intensity pulses at 620 nm, no discernible change in its linear and nonlinear characteristics occurred.

There follow a few remarks regarding the germania-related defect centers which could cause the observed index changes. Based on ESR and optical absorption spectra, the structure

[13] and nature of these defects in high silica glass fibers have been studied. Most of these defects are due to oxygen vacancy sites, which are prevalent in silica fibers due to the very high processing temperatures (>1800°C) used in fiber fabrication. One of the germania-related defects, the so called GeE' center, is of particular interest since it exists or can be induced by exposure to short wavelength radiation [13] at 240 nm. In an oxygen deficient glass, the UV radiation breaks the Ge–Ge covalent bond and liberates an electron, which is then trapped at an oxygen vacancy site. Such defects could modify the glass refractive index through a variety of mechanisms, such as electric field due to trapped electrons or dipoles. Further evidence for this is photosensitivity [16], [17] in germania-doped silica glass optical fibers and a recent report of externally written gratings [18] in similar fibers by a transverse holographic method and 244 nm radiation. In the externally written gratings, the induced refractive index change is estimated to be 3×10^{-5}. However, as the authors [18] point out, if nonuniformity in the grating strength along its length is accounted for, the induced peak index perturbations may be somewhat larger. Considering the differences in the fiber, the irradiation wavelength, and the peak light intensities, our observations agree well with these results. In our experiments, the defects could be generated by multiphoton absorption due to the high intensities (>200 GW/cm^2) used in the switching experiments.

In conclusion, we have reported on the defect associated change of refractive index in germania-doped glass. The change has a pronounced effect on the directional coupler characteristics. The coupler in principle can therefore be used to measure index changes as small as a few parts per million. Furthermore, such defects impose additional constraints on materials for nonlinear optics. For devices, such as couplers, materials should be tailored to avoid them. In others, such as for second harmonic generation and gratings in fibers, it is desirable to enhance their effect. The defect structure of glass is thus becoming an important area of investigation in the search for materials with high nonlinear optical coefficients.

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