RESEARCH ARTICLE | SEPTEMBER 06 2023

Observation of strong photorefractive-like effect in silica micro-fibers

Yue Yan ; Mengpeng Hu; Panpan Sun; Kun Duan ; Qiang Wang ; Wei Ren

AIP Advances 13, 095106 (2023)
https://doi.org/10.1063/5.0159939

Observation of strong photorefractive-like effect in silica micro-fibers

Cite as: AIP Advances 13, 095106 (2023); doi: 10.1063/5.0159939
Submitted: 10 August 2023 • Accepted: 18 August 2023 •
Published Online: 6 September 2023

View Online Export Citation CrossMark

Yue Yan,[1] Mengpeng Hu,[2] Panpan Sun,[2] Kun Duan,[1] Qiang Wang,[2] and Wei Ren[1,a)]

AFFILIATIONS

[1] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong SAR, China
[2] State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, 130033 Changchun, China

[a)] Author to whom correspondence should be addressed: renwei@mae.cuhk.edu.hk

ABSTRACT

We observe the strong photorefractive (PR)-like effect in silica micro-fibers, which is different from the previously reported nonlinear behaviors in optical fiber devices. The micro-fiber is fabricated by tapering a standard silica single-mode fiber using the hydrogen flame. Two fiber Bragg gratings are fused at each end of the micro-fiber to form a Fabry–Pérot cavity, enabling us to observe the nonlinear dynamics. By situating the silica micro-fiber in a gas medium (i.e., N_2, Ar, He, and air), we observe the remarkable PR-like effect, especially under the low-pressure condition below 80 Torr. In fact, the nonlinear effect increases with the reduced pressure as a power function. Such a nonlinear effect is also affected by the laser wavelength detuning rate, input laser power, and micro-fiber diameter. Finally, a nonlinear cavity dynamics model is adopted to well describe the observed nonlinear effect.

Optical nonlinearity has attracted considerable attention in optical fibers[1] and other waveguide devices[2,3] that play important roles in optical communication and sensing.[4,5] The photorefractive (PR) effect is a kind of optical nonlinearity causing the refractive index (RI) to be altered under an internal electric field, which is induced by the photo-excited carrier redistribution.[6] The PR effect shows great potential in applications, such as holography and optical computing,[7,8] but it may limit the performance of devices like high-quality micro-resonators caused by the RI instability of the material.[9,10] To date, the PR effect has been observed in bulk materials, such as lithium niobate ($LiNbO_3$),[11] barium titanate ($BaTiO_3$),[12] and photopolymers,[13] as well as in thin-film devices, such as micro-resonators[10] and photonic crystal.[14]

It should be noted that the PR effect is often observed in asymmetric structural materials that exhibit substantial electro-optic nonlinear effects. Silica is a common optical material with hardly observable effective nonlinearity compared to other crystalline materials. With the advent of low-loss optical fibers that confine light significantly and promise long-distance propagation, a variety of nonlinear phenomena have been studied in silica fiber, such as stimulated Brillouin scattering,[15] stimulated Raman scattering,[16] and self-phase modulation.[17] Another interesting nonlinear behavior on a silica micro-fiber resonator was previously reported that the cavity resonance shows an obvious asymmetry, which can be affected by the laser wavelength detuning rate and input power.[18] Such nonlinearity was explained by the contribution of thermal effect that could be originated from ambient humidity and surface contamination of the micro-fiber.

In this letter, we report the observation of a significant PR-like nonlinear effect in a silica micro-fiber situated in a Fabry–Pérot (F–P) fiber cavity formed by two fiber Bragg gratings (FBGs). The nonlinearity is drastically enhanced when the micro-fiber is placed in a low-pressure environment. We systematically investigate this nonlinear effect by varying the wavelength detuning rate, input laser power, gas environment, and micro-fiber diameter. Furthermore, a nonlinear cavity dynamics model is adopted to describe the observed effect.

Figure 1 depicts the schematic of the experimental setup for observing the PR-like nonlinear effect in a silica micro-fiber. The micro-fiber was fabricated by stretching a silica single-mode fiber

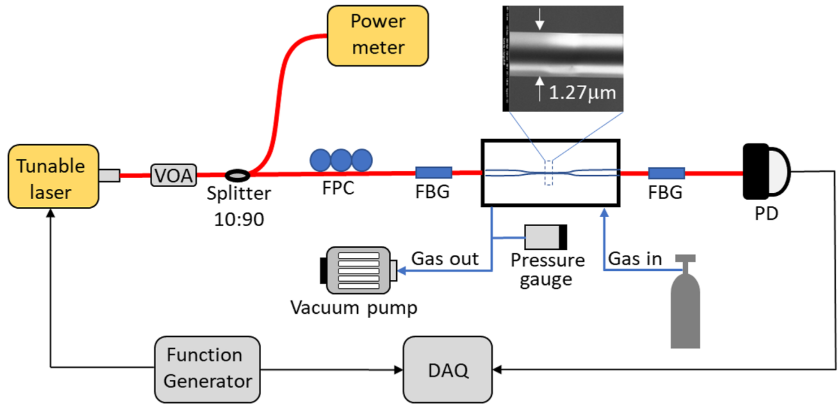

FIG. 1. Experimental setup of observing the nonlinear effect in a silica micro-fiber. VOA: variable optical attenuator; FPC: fiber polarization controller; FBG: fiber Bragg grating; DAQ: data acquisition; and PD: photodetector. Inset: scanning electron microscopy image of a silica micro-fiber with a diameter of 1.27 μm.

(Corning, SMF-28e+) using the hydrogen flame, enabling the generation of a tapered fiber with a controlled waist diameter and length. The fiber cavity has a low finesse of ~11 and a free space range (FSR) of 0.73 pm. Considering the coupling efficiency of the laser into the cavity is as low as 1%, the intra-cavity power is evaluated to be 0.4 mW. The micro-fiber was sealed in a stainless-steel cell ($8 \times 3 \times 2$ cm^3) that can be filled with gas samples with controllable components and pressures as required. Two FBGs (reflectivity: 99.7% at 1550 ± 3 nm) were spliced at each end of the micro-fiber to form an F–P cavity. A tunable laser (wavelength: 1550 nm, linewidth: 1.7 kHz) was connected to the cavity via a splitter (10:90), which separated a small portion of the light to a power meter for monitoring purposes. A fiber polarization controller (FPC) was used to minimize the birefringence. Finally, the transmitted light was detected by a photodetector (Thorlabs, PDA20CS-EC). During the experiment, the laser wavelength was scanned over the cavity mode by a triangle waveform; the forward scan corresponds to blue-to-red, and the backward scan corresponds to red-to-blue.

Figure 2(a) demonstrates the cavity-transmission signal by scanning the laser wavelength forward and backward across one cavity mode under different gas pressures. It should be noted that the cavity mode may drift due to environmental disturbance, so we manually shift the resonance center of the cavity mode for comparison purposes. Here, pure nitrogen (N_2) was filled in the gas cell. At the pressure >80 Torr, the cavity mode shows a Lorentzian line-shape without significant distortion. However, when the gas pressure in the cell is reduced gradually, the cavity mode profile shows an evident broadening during the forward laser scan (or compression during the backward laser scan). Additionally, the resonance center shifts to a longer wavelength when the laser wavelength approaches the resonance center of the cavity mode from the blue-detuned side, producing a positive ramp-like resonance line-shape that indicates an increase in the RI of the silica micro-fiber. At first glance, we thought this strong nonlinear behavior might belong to the thermo-optic effect as silica has a positive thermo-optic coefficient of 1.09×10^{-5} K^{-1}.[19] This conjecture was overthrown as the optical loss of the SMF-28e+ fiber is less than 0.2 dB/km at 1550 nm, leading to negligible absorption-induced thermal nonlinearity. Note that gas absorption by the evanescent-wave does not exist in the cell that is filled with zero-absorption N_2. We further conducted a detailed analysis of the thermo-optic effect in the micro-fiber (see supplementary material), showing the negligible contribution to the observed nonlinearity. Dispersion can also shape the cavity modes. However, the dispersion of the SM-28e+ fiber is ≤18 ps/(nm km), which is too small to produce such a significant cavity mode distortion.

Instead, such a strong nonlinearity is more consistent with the PR effect. To further test our hypothesis, we investigated the PR-like effect by varying the wavelength detuning rate and power level of the laser. As shown in Fig. 2(b), the nonlinear effect is weaker with the increased laser scan rate. The result indicates a limited nonlinear relaxation time at the milli-second scale (see discussion in the following section), which is similar to the case observed in lithium niobate.[10,20] Figure 2(c) shows that the PR-like effect is mitigated with the decreased laser power, which is not surprising as it is hard for the low optical power to induce the internal electric field.

The silica micro-fiber exhibits a stronger PR-like effect with a smaller diameter. Figure 3(a) compares the transmission signal by varying the micro-fiber diameter from 1.27 to 3 μm. A stronger nonlinearity is observed for a thinner fiber due to the larger laser power intensity. Furthermore, we also investigated the possible effects of filling different gases in the gas cell. Figure 3(b) compares the scanned cavity modes with the gas cell filled by N_2, argon (Ar), helium (He), and air; the gas pressure is 5 Torr, the laser scan rate is 2.5 Hz, and the input laser power is 11 mW. The results reveal that the cavity mode remains almost the same, indicating the negligible influence of gas species on the nonlinear effect.

It is of interest to explore the possible reasons for observing the PR-effect, which may be relevant to the micro-fiber fabrication process. The fiber stretching in the hydrogen flame may alter the polarization of the silica material similar to the thermal poling,[21] resulting in an increased second-order optical nonlinear coefficient $\chi^{(2)}$. The non-uniform distribution of the laser intensity inside the

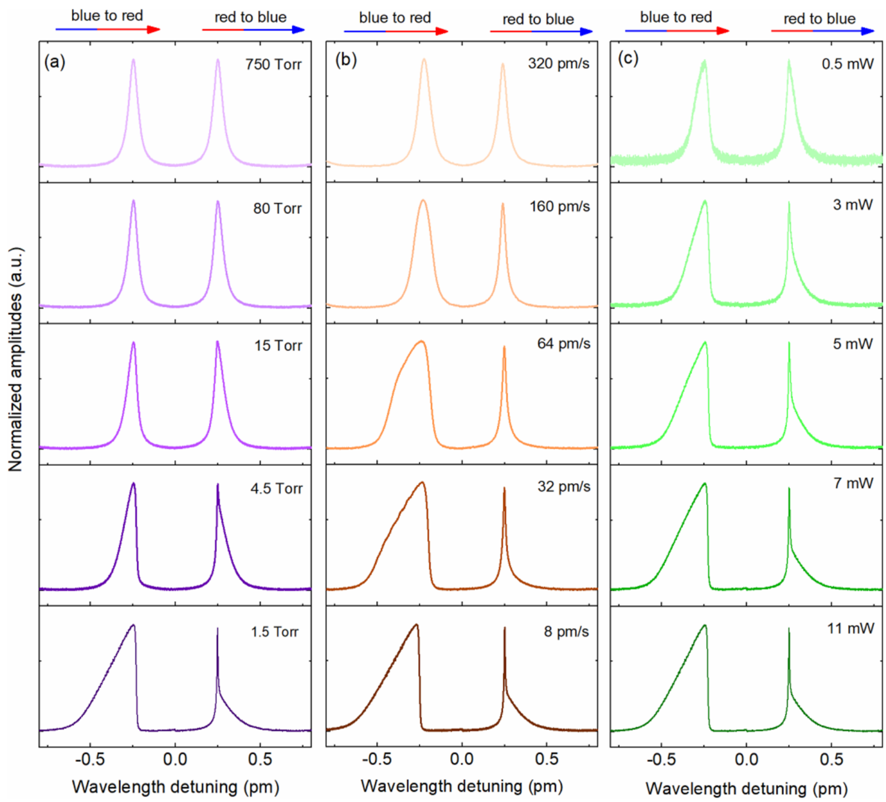

FIG. 2. Transmission signal of the forward and backward scanned laser passing through the silica micro-fiber F–P cavity under different experimental conditions. (a) Variation of transmission signal with gas pressure under the fixed laser scan rate of 2.5 Hz and a laser power of 11 mW. (b) Variation of transmission signal with the laser scan rate under the fixed gas pressure of 1.5 Torr and an input laser power of 11 mW. (c) Variation of transmission signal with input laser power under the fixed gas pressure of 1.5 Torr and a laser scan rate of 2.5 Hz.

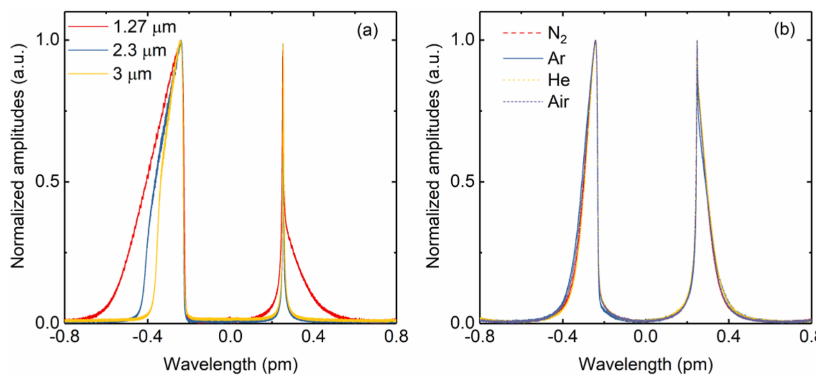

FIG. 3. Forward and backward laser-scanned transmission signal measured under (a) varied micro-fiber diameters (pressure 1.5 Torr, laser scan rate 2.5 Hz, and input laser power 11 mW) and (b) varied gas conditions (pressure 5 Torr, laser scan rate 2.5 Hz, and input laser power 11 mW).

micro-fiber could cause carrier excitation and migration from the impurity level, thus introducing a strong internal electric field and the subsequent RI change by the Pockels effect. The low-pressure environment possibly changes the silica–gas interface, which could affect the carrier excitation and migration process[22] or even enhance the second-order nonlinearity by the surface dipole effect.[9] However, we believe that the underlying physical nature needs further exploration.

It is known that the PR effect can be described by the equation of motion of cavity dynamics as[10,23]

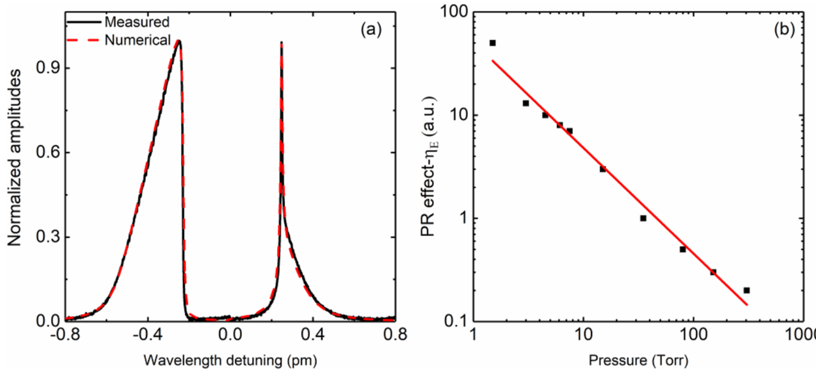

FIG. 4. (a) Measured PR-like effect of the silica micro-fiber and its numerical fitting (fiber diameter 1.27 μm, laser scan rate 8 pm/s, pressure 1.5 Torr, and input laser power 11 mW). (b) Variation of the η_E coefficient with gas pressure.

$$\frac{da}{dt} = \left(i\Delta_0 - \frac{\Gamma_t}{2}\right)a - iEa + i\sqrt{\Gamma_e}A, \tag{1}$$

$$\frac{dE}{dt} = -\Gamma_E E + \eta_E |a|^2, \tag{2}$$

where a and A are the amplitudes of the intracavity field and the input field, respectively; Δ_0 is the detuning of the laser frequency w with respect to the cavity resonance w_0; Γ_t and Γ_e are the photon decay rate and external decay rate of the cavity, respectively; E is the resonance frequency shift due to the PR effect; and Γ_E and η_E are the relaxation rate and strength coefficient of the PR effect, respectively. Equations (1) and (2) describe the cavity dynamics due to the PR effect so that we could fit the unknown parameters Γ_E and η_E from the recorded transmission spectra. Figure 4(a) shows the simulation result using the dynamic cavity mode for a fiber diameter of 1.27 μm. The model well describes the PR-like effect inside the F–P fiber cavity, showing that the relaxation rate Γ_E (250 Hz) is much smaller than the relaxation rate of the thermo-optic effect (100 kHz) in the $LiNbO_3$ micro-resonator.[10] Some other assumptions like two-photon absorption and free carrier absorption could also be excluded since those effects are produced even faster on the gigahertz scale.[24] Based on the cavity dynamics, we are able to quantitatively describe the relationship between the coefficient η_E and pressure, as shown in Fig. 4(b), which shows that the PR-like effect increases with the reduced pressure as a power function.

In summary, we present the observation of the significant PR-like effect existing in a silica micro-fiber placed in a low-pressure gas medium. The observed PR-like nonlinear effect increases nearly in a power function with the reduced gas pressure and increases with a slower laser scan rate, stronger input laser power, and smaller micro-fiber diameter. However, this nonlinear effect shows little influence by different types of gas medium (i.e., N_2, Ar, He, and air). The standard model of nonlinear cavity dynamics was adopted to well describe the observed PR-like effect. However, the exact mechanism behind this nonlinear phenomenon deserves further study in silica thin films and other materials in the future. Moreover, the demonstrated F–P cavity with a micro-fiber can be used as a highly sensitive interferometer for chemical sensing applications. We believe the observation reported in this letter may also bring opportunities for holography and optical computing on silica fibers and integrated photonics circuits.

The supplementary material provides a detailed analysis of the possible thermo-optic effect in the micro-fiber.

This work was supported by the General Research Fund (Grant Nos. 14209220 and 14208221), Hong Kong SAR, China, and the National Natural Science Foundation of China (NSFC) (Grant No. 62005267).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Yue Yan: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Mengpeng Hu**: Resources (equal). **Panpan Sun**: Resources (equal). **Kun Duan**: Investigation (equal). **Qiang Wang**: Resources (equal). **Wei Ren**: Formal analysis (equal); Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] G. P. Agrawal, J. Opt. Soc. Am. B **28**(12), A1 (2011).
[2] J. Leuthold, C. Koos, and W. Freude, Nat. Photonics **4**(8), 535 (2010).
[3] D. Sun, Y. Zhang, D. Wang, W. Song, X. Liu, J. Pang, D. Geng, Y. Sang, and H. Liu, Light: Sci. Appl. **9**(1), 197 (2020).

[4]P. Lu, N. Lalam, M. Badar, B. Liu, B. T. Chorpening, M. P. Buric, and P. R. Ohodnicki, Appl. Phys. Rev. **6**(4), 041302 (2019).
[5]E. Garmire, Opt. Express **21**(25), 30532 (2013).
[6]T. J. Hall, R. Jaura, L. M. Connors, and P. D. Foote, Prog. Quantum Electron. **10**(2), 77 (1985).
[7]J. Li and H. Fan, Opt. Lasers Eng. **120**, 79 (2019).
[8]C. Gu, Y. Xu, Y. Liu, J. J. Pan, F. Zhou, and H. He, Opt. Mater. **23**(1–2), 219 (2003).
[9]Y. Xu, M. Shen, J. Lu, J. B. Surya, A. A. Sayem, and H. X. Tang, Opt. Express **29**(4), 5497 (2021).
[10]X. Sun, H. Liang, R. Luo, W. C. Jiang, X.-C. Zhang, and Q. Lin, Opt. Express **25**(12), 13504 (2017).
[11]L. Razzari, P. Minzioni, I. Cristiani, V. Degiorgio, and E. P. Kokanyan, Appl. Phys. Lett. **86**(13), 131914 (2005).
[12]G. A. Brost, R. A. Motes, and J. R. Rotge, J. Opt. Soc. Am. B **5**(9), 1879 (1988).
[13]B. A. Kowalski and R. R. McLeod, J. Polym. Sci., Part B: Polym. Phys. **54**(11), 1021 (2016).
[14]M. Li, H. Liang, R. Luo, Y. He, and Q. Lin, Laser Photonics Rev. **13**(5), 1800228 (2019).
[15]E. P. Ippen and R. H. Stolen, Appl. Phys. Lett. **21**(11), 539 (1972).
[16]R. H. Stolen, C. Lee, and R. K. Jain, J. Opt. Soc. Am. B **1**(4), 652 (1984).
[17]R. H. Stolen and C. Lin, Phys. Rev. A **17**(4), 1448 (1978).
[18]G. Vienne, Y. Li, L. Tong, and P. Grelu, Opt. Lett. **33**(13), 1500 (2008).
[19]H. Gao, Y. Jiang, Y. Cui, L. Zhang, J. Jia, and L. Jiang, J. Lightwave Technol. **36**(24), 5881 (2018).
[20]H. Liang, R. Luo, Y. He, H. Jiang, and Q. Lin, Optica **4**(10), 1251 (2017).
[21]V. Pruneri, F. Samoggia, G. Bonfrate, P. G. Kazansky, and G. M. Yang, Appl. Phys. Lett. **74**(17), 2423 (1999).
[22]Y. Kanemitsu and S. Imamura, J. Appl. Phys. **67**(8), 3728 (1990).
[23]A. E. Fomin, M. L. Gorodetsky, I. S. Grudinin, and V. S. Ilchenko, J. Opt. Soc. Am. B **22**(2), 459 (2005).
[24]T. Van Vaerenbergh, M. Fiers, P. Mechet, T. Spuesens, R. Kumar, G. Morthier, B. Schrauwen, J. Dambre, and P. Bienstman, Opt. Express **20**(18), 20292 (2012).