Observation of a Push Force on the End Face of a Nanometer Silica Filament Exerted by Outgoing Light

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There are two different proposals for the momentum of light in a transparent dielectric of refractive index n: Minkowski's version nE/c and Abraham's version $E/(nc)$, where E and c are the energy and vacuum speed of light, respectively. Despite many tests and debates over nearly a century, momentum of light in a transparent dielectric remains controversial. In this Letter, we report a direct observation of the inward push force on the free end face of a nanometer silica filament exerted by the outgoing light. Our results suggest that Abraham's momentum is correct.

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The momentum of light in dielectrics is one of Rudolf Peierls's classic surprises in theoretical physics [1,2]. In a transparent dielectric of refractive index n, Minkowski suggested nE/c for the momentum of light [3], whereas Abraham suggested $E/(nc)$ for the same physical quantity [4], where E and c are the energy and vacuum speed of light, respectively. There are many theories to clarify these two momenta [5–22], but the number of experimental tests is small [23–26]. One of the experimental tests by observing the radiation pressure at the water-air interface [23] is now reckoned to support Abraham momentum [2]. On the other hand, the measurement of systematic shift in the photon recoil frequency due to the index of refraction of the Bose-Einstein condensate suggested that Minkowski momentum is correct [24]. Furthermore, the experiment of the light pressure on a mirror suspended in water appeared to support Minkowski momentum [25], but the careful calculation of a total transferred momentum of light beam in the form of a short single-photon pulse fit Abraham's value [11]. A similar case was the experiment of photon drag effect in semiconductors [13,16,26]. Despite the tests and debates over nearly a century, the controversy of momentum of light in dielectrics remains [2]. The main difficulty is experimental identification of light momentum in a transparent dielectric [1,2]. The complexity of momentum transfer of light in the dielectric obstructs the direct observation of light momentum, making experimental interpretations ambiguous. The way to observe light momentum in a lossless transparent dielectric by exploring the light pressure on the surfaces of a parallel-sided block of dielectric in air or in vacuum was shown to be unpromising [9]. The beautiful idea proposed by Ashkin and Dziedzic on the experiment of radiation pressure at the single water-air interface [23] also encountered difficulty. Here we briefly review their idea and experiment. According to Abraham momentum, when light normally enters (or leaves) a lossless nonmagnetic transparent dielectric through its free surface, the decrease (or increase) of light momentum due to transmission and specular reflection at the surface is $2E/c(n-1)/(n+1)$ [or $2E/(nc)\times(n-1)/(n+1)$] if $n>1$, where E is the energy of light incident onto the surface. By conservation of momentum, the surface of the dielectric will gain (or lose) a momentum $2E/c(n-1)/(n+1)$ [or $2E/(nc)(n-1)/(n+1)$] from (or to) the light and experience an inward radiation pressure for both cases of the light entering and leaving (the effect is also predicted by Loudon's theory based on the Lorentz force [11]). In contrast, Minkowski momentum predicts that, when light normally enters (or leaves) the dielectric, the free surface will have a momentum change of $2E/c(n-1)/(n+1)$ [or $2nE/(c)(n-1)/(n+1)$] pointing to outside and experience an outward radiation pressure. Ashkin and Dziedzic's idea was simple: Abraham (Minkowski) momentum would result in an inward (outward) movement of the free surface of a liquid. In their experiment, Ashkin and Dziedzic observed an outward bulge on the water-air interface when a light enters (or leaves) the water, which appeared to support Minkowski momentum. However, the bulge of water surface was found to be due to the lateral dipole forces caused by the intensity gradient of a Gaussian beam, which conceals the effect of light momentum [6,13]. We have found a way to overcome this difficulty by replacing the water surface by a nanometer silica filament (SF) and letting light travel in the SF and then emerge into air or vacuum from the free end of the SF. It was based on such an idea: As a SF is a solid and so lithe, its free end will be pushed to move backward if Abraham momentum applies or be pulled forward if Minkowski momentum applies, when light emerges from the free end. In this Letter, we report direct observation of a push force on the end face of the SF exerted by the outgoing light. Our experimental results suggest that Abraham momentum is correct.

The silica filaments used in our experiments are fabricated with single-mode fibers (SMF-28, from Corning Company), by a technique reported in [27]. Figure 1 elucidates the stationary micrograph of the tip of the first SF for observing optical force. It is taken by a microscope

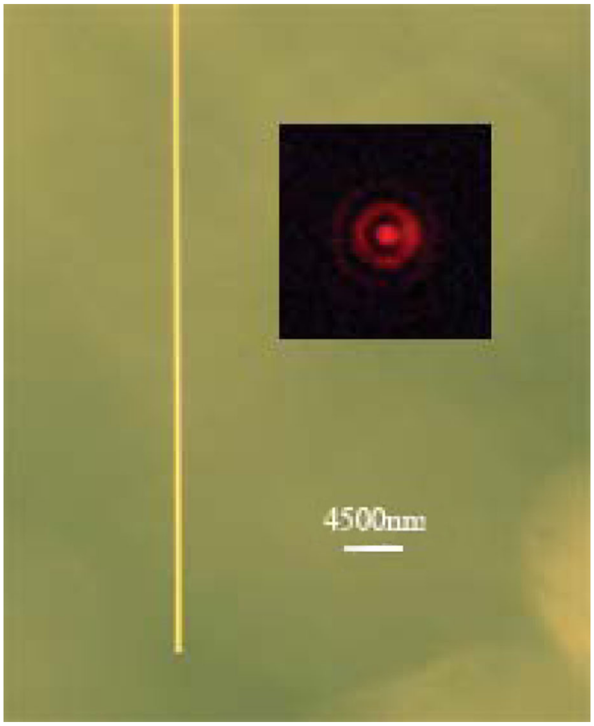

FIG. 1 (color online). The stationary micrograph of the tip of the SF, showing that the diameter of the SF tip is about 450 nm. The inset is the enlarged profile of a weak red light beam outgoing from the SF end face.

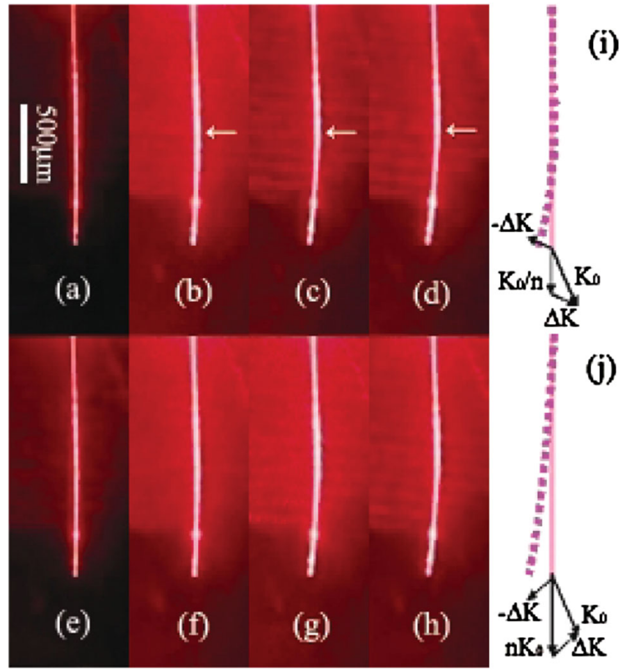

FIG. 2 (color). The video frames of the moving SF as the result of the optical force for the SF in air, where (a), (b), (c), and (d) are the images of SF at 0, $1/15$, $2/15$, and $3/15$ s, respectively, after a laser pulse arrives, and (e), (f), (g), and (h) correspond to the next laser pulse. Figures (i) and (j) show the effect of asymmetric refraction related, respectively, to Abraham momentum $\mathbf{K_0}/n$ and Minkowski momentum $n\mathbf{K_0}$, where $\mathbf{K_0}$ is the vacuum momentum of light and $\Delta\mathbf{K}$ $(-\Delta\mathbf{K})$ is the momentum change of light (SF end). Pink solid and dashed lines in (i) and (j) indicate two different states of the SF.

(Hisomet II DH2 series, from Union Optical Co., Ltd.), showing that the diameter of the tip is about 450 nm. The inset in Fig. 1 is the enlarged profile of a weak 650 nm light beam outgoing from the end face of SF. It is taken by the same microscope, showing that the end face is almost a round one and there has no observable forward asymmetric scattering.

The light source is a 650 nm unpolarized semiconductor laser with a fiber connector, which can operate at either pulse or cw mode with 10 mW peak or cw power. At pulse mode, the full pulse duration is about $4/15$ s, and each dark interval is about $1/5$ s. The laser pulses are coupled into a 2 m long fiber with a SF drawn from the free end of the fiber. The SF is mounted in a hermetic flat-circinal-shape glass chamber with a diameter of 10.5 cm to avoid the influence of the flowing air. The space from the top (or bottom) of the glass chamber to the SF is about 1 cm. We erect the glass chamber and let the SF come down naturally like that shown in Fig. 2(a). The movement of the SF is taken by a digital camera (Canon G5), which is set at movie mode with a rate of 15 frames/s. A quartz plane-convex lens is inserted between the glass chamber and the camera for taking the suitably large, clear image of the moving SF. The coupled-in power is measured by cutting the fiber and taking off its coating after experiment. Figures 2(a)–2(h) display video frames of the moving SF of 1.5 mm as the result of the optical force, where (a), (b), (c), and (d) are the images of SF at 0, $1/15$, $2/15$, and $3/15$ s, respectively, after a laser pulse arrives, and (e), (f), (g), and (h) correspond to the next laser pulse. The coupled-in peak power is 6.4 mW, and room temperature is 27 °C. Figures 2(a)–2(h) show clearly that, when a laser pulse arrives, the SF end moves to left-upwards and the part of the SF pointed out by a white arrow moves to the right; when the laser pulse disappears, the SF comes back to its original state in no more than $1/5$ s; when the next laser pulse arrives, the SF moves again [see Figs. 2(e)–2(h)]. (More details can be viewed in the video [28].)

The purpose of measuring the transmission of the SF P_T, the transmission plus scattering of the SF $P_{T\&S}$, and the transmission of cut bare single-mode fiber P_{Fib} is to eliminate the possible influence of scattering of light on the phenomenon observed. The detector used is a universal optical power meter (13 PDC 001, from MELLES GRIOT) with a 5MM integrating sphere. Figure 3(a) shows the experimental results obtained with 650 nm cw laser and at 27 °C, from which we calculate that $P_T = 6.1547 \pm 0.0007$ mW, $P_{T\&S} = 6.1981 \pm 0.0003$ mW, and $P_{\mathrm{Fib}} = 6.1973 \pm 0.0001$ mW, which suggest that the thermal loss of the SF is small and the loss of the SF is mainly

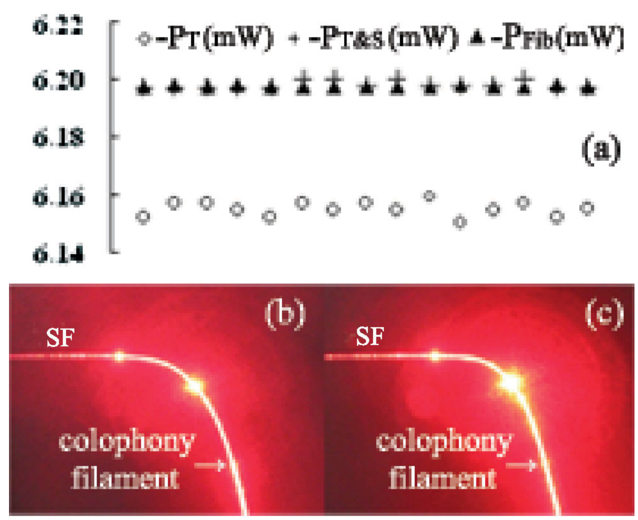

FIG. 3 (color online). (a) The measurements for the transmission of SF P_T, the transmission plus scattering of SF $P_{T\&S}$, and the transmission of a cut bare single-mode fiber P_{Fib}. (b), (c) The experiment of thermal effect of the SF: A colophony filament with 3 μm diameter is adhered on the SF tip. The overlap of the colophony filament and SF is between two bright spots. The coupled-in power of cw 650 nm light is 6.5 mW. The time intervals for (b) and (c) are, respectively, 1 and 60 minutes after turning on the laser. The room temperature is 27 °C.

due to the elastic scattering of light (the light intensity is only 3.9×10^6 W/cm^2), being about 0.7%. Therefore, for a 6.4 mW coupled-in power, the scattering is only 0.045 mW, too weak to result in an observable movement of the SF like those shown in Fig. 2.

A further experiment is done to eliminate possible influence of the thermal effect on the phenomenon observed. This experiment is carried out by using a colophony filament with 3 μm diameter, adhered on the SF tip. Figures 3(b) and 3(c) show the result obtained at a room temperature of 27 °C, where (b) and (c) correspond, respectively, to 1 and 60 minutes after turning on the laser. The coupled-in power of 650 nm is 6.5 mW at cw mode. The overlap of the colophony filament and SF is between two bright spots. No dropping of the colophony filament after 60 minutes shows clearly that the temperature of the SF was below 300 °C, the decomposition temperature of colophony. We know from Fig. 2 that the SF reacts in less than $2/15$ s when a laser pulse arrives, and during this time interval the temperature change of the SF should be far less than 273 °C. So the thermal expansion of a 1.5 mm SF calculated should be far less than 0.2 μm for a small thermal expansion coefficient of the SF, 5×10^{-7} °C^{-1} [29]. Such a thermal expansion cannot result in an observable movement of the SF like those shown in Fig. 2.

The phenomenon described above is also observed with other SFs. In another experiment we use a SF in a vacuum of 2×10^{-5} Torr at 20 °C and with an electrostatic shield to show that the phenomenon is independent of air and static electricity. Instead of a 650 nm laser, here a power-tunable unpolarized cw 980 nm semiconductor laser is used to drive the SF highlighted by a 0.1 mW cw 650 nm light. Figures 4(a)–4(e) display video frames of the moving SF as the result of the optical force, where Fig. 4(a) corresponds to no 980 nm light coupled in. Figure 4(f) is the micrograph of the SF tip, showing that the diameter of it is about 520 nm. We observe that, when the coupled-in power of 980 nm light is tuned to 17.8 mW, the SF end moves to the right with a displacement of about 30 μm as shown in Fig. 4(b); when the power is increased further to 19.5 mW, it swings thrice [(b) to left (c), then to right (d), then to left (e)] in a time of 1.9 s.

From the experiments described above, we believe that the phenomenon observed is due to the force exerted by the outgoing light. The nature of SF movement cannot be explained by Minkowski momentum. Minkowski momentum predicts a pull force, which pulls the whole SF to one side for asymmetric refraction [see Fig. 2(j)] or pulls it straight for direct transmission. This is not the case observed. However, the movements shown in Figs. 4(a)–4(e) can be explained by direct transmission of light related to Abraham momentum. It predicts a push force perpendicular to the end face of the SF in this case. The force component perpendicular to the axes of the top part of the SF drives the SF to move to the left (right) when the SF is bent slightly to the right (left) as seen. Let us focus on Figs. 4(a) and 4(b) for further analysis.

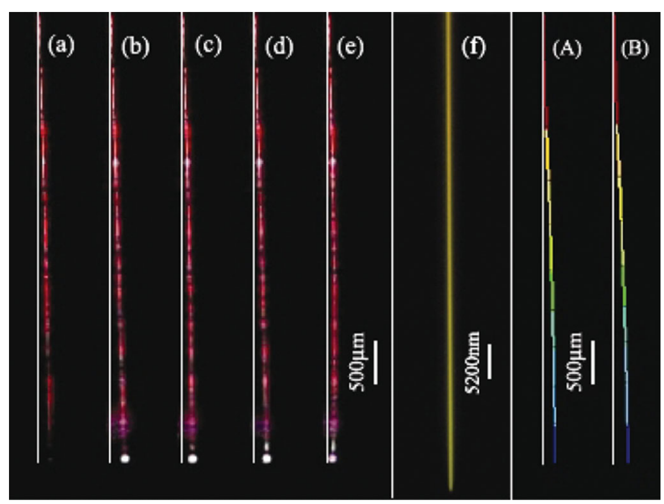

FIG. 4 (color). The video frames of the moving SF as the result of the optical force for the SF in a vacuum of 2×10^{-5} Torr at 20 °C with an electrostatic shield. The SF is driven by a power-tunable, unpolarized cw 980 nm light and highlighted by a 0.1 mW cw 650 nm light. (a) No 980 nm light is coupled in; (b) the coupled-in power of 980 nm is 17.8 mW; (c)–(e) the power is increased further to 19.5 mW in a time of 1.9 s; (f) the micrograph of the SF tip. Figures (A) and (B) are the results of the numerical simulations, with (A) corresponding to the initial state (a) and (B) corresponding to (b). The white vertical lines are for displacement reference.

Figures 4(A) and 4(B) show the numerical results of static analysis simulated by the finite element method (using ANSYS 6.0), where (A) corresponds to the initial state Fig. 4(a) of the SF under gravity and (B) corresponds to the state Fig. 4(b) of the SF under optical force and gravity. The SF parameters for simulation are, respectively, length $L = 5$ mm, diameter $d = 520$ nm, density $\rho = 2.2\ \mathrm{g/cm^3}$ [30], Young's elastic modulus $Y = 70$ GPa [31], and refractive index $n = 1.451$ from the Sellmeier formula [32]. In addition, the optical push force is given by $f_A = 2P/(nc)(n-1)/(n+1)$ according to the momentum change of the light at the surface of the dielectric as discussed earlier, where P is the power of light traveling to the SF end, which is set at zero for Fig. 4(A) and 17.9 mW for Fig. 4(B). The calculated displacement of SF end for Fig. 4(B) is 29 μm. We see that the numerical simulation is consistent with the experiment. On the other hand, Figs. 2(a)–2(h) can also be understood by asymmetric refraction of light related to Abraham momentum [see Fig. 2(i)]. According to the cantilever beam theory in strength of materials, the SF end makes a horizontal displacement of $\Delta x = f_x(64L^3)/(3\pi Y d^4)$ when it is pushed by the component of optical force $f_x = f_A \sin\alpha$, where α is the angle between the optical force $\mathbf{f}_A$ and the axes of the top part of the SF. For the SF shown in Fig. 2, $d = 450$ nm, $L = 1.5$ mm, $Y = 70$ GPa, $n = 1.457$, $P = 6.4$ mW, and the observed displacement $\Delta x \approx 9\ \mu$m [Fig. 2(a), 2(b), 2(e), and 2(f)], the value of α fitted is about 12.13°, which suggests the end face of the SF is inclined with an angle of about 8°. The reason for choosing Figs. 2(a), 2(b), 2(e), and 2(f) for the calculation is that α is almost a constant and the kinetic energy of the SF at the state Figs. 2(b) and 2(f) is small and is ignored. The quantitative analysis of Figs. 2(c), 2(d), 2(g), and 2(h) is more complex, needing to be investigated further.

In conclusion, our experiment and analysis suggest that Abraham momentum is correct. Furthermore, our experiment also suggests a potentially important application of the momentum of light. As discussed above, when light is incident on the surface of a transparent dielectric from vacuum, it exerts an inward pressure on the surface of the dielectric. This pressure is different from the commonly recognized one due to the specular reflection. Therefore, when a series of incoherent laser beams with almost constant diameters is simultaneously incident on the surface of a transparent dielectric ball in vacuum along the radial direction, the dielectric ball will shrink due to the effect of Abraham momentum. This effect may be useful for the precise design of the laser-induced inertially confined fusion.

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[1] R. Peierls, *More Surprises in Theoretical Physics* (Princeton University Press, Princeton, NJ, 1991).
[2] U. Leonhardt, Nature (London) **444**, 823 (2006).
[3] H. Minkowski, Nachr. Kön. Ges. Wiss. Gött. Math.-Phys. Kl. 53 (1908).
[4] M. Abraham, Rend. Circ. Mat. Palermo **28**, 1 (1909).
[5] M. G. Burt and R. Peierls, Proc. R. Soc. A **333**, 149 (1973).
[6] J. P. Gordon, Phys. Rev. A **8**, 14 (1973).
[7] R. Peierls, Proc. R. Soc. A **355**, 141 (1977).
[8] R. Loudon, L. Allen, and D. F. Nelson, Phys. Rev. E **55**, 1071 (1997).
[9] R. V. Jones, Proc. R. Soc. A **360**, 365 (1978).
[10] D. F. Nelson, Phys. Rev. A **44**, 3985 (1991).
[11] R. Loudon, J. Mod. Opt. **49**, 821 (2002).
[12] Y. N. Obukhov and F. W. Hehl, Phys. Lett. A **311**, 277 (2003).
[13] R. Loudon, Fortschr. Phys. **52**, 1134 (2004).
[14] M. A. López-Mariño and J. L. Jiménez, Found. Phys. Lett. **17**, 1 (2004).
[15] A. Feigel, Phys. Rev. Lett. **92**, 020404 (2004).
[16] R. Loudon, S. M. Barnett, and C. Baxter, Phys. Rev. A **71**, 063802 (2005).
[17] M. Mansuripur, Opt. Express **13**, 2245 (2005).
[18] R. Loudon and S. M. Barnett, Opt. Express **14**, 11 855 (2006).
[19] U. Leonhardt, Phys. Rev. A **73**, 032108 (2006).
[20] M. Mansuripur, Opt. Express **15**, 2677 (2007).
[21] T. Dereli, J. Gratus, and R. W. Tucker, J. Phys. A **40**, 5695 (2007).
[22] T. Dereli, J. Gratus, and R. W. Tucker, Phys. Lett. A **361**, 190 (2007).
[23] A. Ashkin and J. M. Dziedzic, Phys. Rev. Lett. **30**, 139 (1973).
[24] G. K. Campbell *et al.*, Phys. Rev. Lett. **94**, 170403 (2005).
[25] R. V. Jones and B. Leslie, Proc. R. Soc. A **360**, 347 (1978).
[26] A. F. Gibson *et al.*, Proc. R. Soc. A **370**, 303 (1980).
[27] L. Tong *et al.*, Nature (London) **426**, 816 (2003).
[28] See EPAPS Document No. E-PRLTAO-101-056849 for the video of the movement of a SF in air taken by a camera at a rate of 15 frames/s. The coupled-in peak power of 650 nm light pulses is 6.4 mW. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.
[29] P. K. Bachmann, D. U. Wiechert, and T. P. M. Meeuwsen, J. Mater. Sci. **23**, 2584 (1988).
[30] H. S. Seo *et al.*, J. Lightwave Technol. **16**, 2355 (1998).
[31] E. C. C. M. Silva *et al.*, Small **2**, 239 (2006).
[32] L. Tong, J. Lou, and E. Mazur, Opt. Express **12**, 1025 (2004).