# All-Optical Full-Color Displays Using Polymer Nanofibers

**Huaqing Yu,[†] Dongwei Liao,[†] Michael B. Johnston,[‡] and Baojun Li[†,*]**

[†]State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics and Engineering, Sun Yat-Sen University, Guangzhou 510275, China, and [‡]Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom

**ABSTRACT** We report a number of crossed nanofiber structures for full-color micro/nanodisplays, which were formed by assembling flexible poly(trimethylene terephthalate) (PTT) nanofibers under an optical microscope with the assistance of micromanipulators. The color pixels of the displays consist of micro/nanometer sized color spots in a radius of 300−1500 nm, which were realized through crossed junctions of the PTT nanofibers. The colors of the spots were tuned by changing the power ratios of the launched red, green, and blue lights. We further present a new way to develop white light illumination by combination of red, green, and blue lights with assembly techniques and low production costs.

**KEYWORDS:** color display · nanofiber · polymer · all-optics · nanophotonics

Electrically driven liquid-crystal displays are now ubiquitous components of consumer electronics, and even more efficient "electrophoretic ink and electrowetting" displays[1,2] are currently being commercialized. Recently, color displays have been developed from a range of nanomaterials such as nanowires[3−6] and nanofibers.[7−10] With the rapid progress of nanoscience and nanotechnology, crossed nanowires were used as basic elements for multicolor light emitting diodes.[3] At the same time, core/multishell nanowire heterostructures were also used as multicolor and high efficiency light-emitting diodes (LEDs).[4] Recently transparent active matrix LED displays were demonstrated,[5] which were driven by a nanowire transistor circuit with low drive voltages (forward bias, about 3.5 V). To avoid the use of an electrically driven method, investigations on optically controlled color displays (*i.e.*, all-optical full-color displays) based on different materials are extremely important and desired. Polymer materials have been the subject of intense investigation and are promising for full-color screens due to their good processability, high flexibility, and low-cost.[7] Particularly, poly(trimethylene terephthalate) (PTT) possesses strong flexibility and more than 90% elastic recovery,[11] relatively large refractive index (1.638),[12] and good transparency from visible lights to near-infrared.[13] These properties make PTT material suitable for photonics and miniaturized photonic devices.[14] Moreover, optical transmission loss of PTT nanofiber is smaller than that of $SnO_2$ nanoribbon[15] and comparable with that reported for silica nanofiber.[16] This imply that the device performances of the PTT nanofibers are better than those of the silica nanofibers. Therefore, in this work, we demonstrate all-optical full-color displays using flexible PTT nanofibers. Different colors were achieved through color-mixing technique and tuned by changing the power ratios of red, green, and blue (RGB) lights. The saturation and brightness of the displays were adjusted by simply changing the powers of the incoming RGB lights.

The nanofibers we used in this work to assemble display structures were drawn by a simple one-step direct drawing process from the PTT melt.[13] In the experiment, the PTT nanofibers were carefully manipulated with the help of a micromanipulator under an optical microscope. First, a simply crossed structure was assembled on a cleaned glass substrate (refractive index, 1.50) by crossing the nanofiber 2 on the top of the nanofiber 1 as shown by the scanning electron microscope (SEM) image (Figure 1a). The diameters of the nanofibers 1 and 2 are 457 and 486 nm, respectively. The crossing angle of nanofibers 1 and 2 is 85°. It should be mentioned that, normally, to get a maximum coupling efficiency in evanescent wave coupling between two nanofibers, the two nanofibers must be placed in parallel and contact each other.[17] But in this work, the key elements are junctions formed by crossing nanofibers with a suitable crossing angle. For specified wavelengths and fixed diameters of nanofibers, the coupling efficiency between the crossed nanofibers will be lower for a larger crossing angle.[17]

* Address correspondence to stslbj@mail.sysu.edu.cn.

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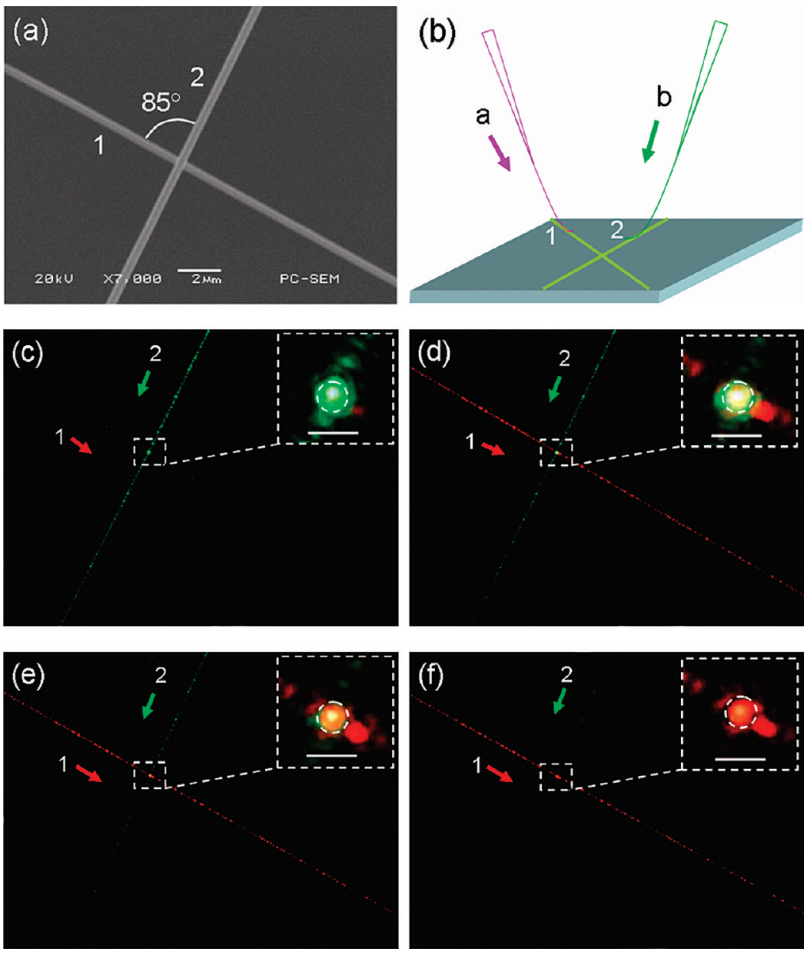


**Figure 1. Images of a crossed structure assembled using two PTT nanofibers and optical coupling method. (a) SEM image of the two PTT nanofibers with diameters of 457 nm (nanofiber 1) and 486 nm (nanofiber 2). Crossing angle of the nanofibers 1 and 2 is 85°. (b) Schematic of optical coupling method by evanescent wave through silica fiber tapers a and b. (c−f) Optical microscope images of the mixed colors at the junction of the structure. The insets show zoomed (×10) views of the spots at crossed junctions. The arrows show the propagation directions of the lights. Scale bars in the insets of panels c−f are 10 μm.**

To decrease coupling of propagation light between the crossed nanofibers and keep more lights at these junctions, the crossing angle of these structures is kept larger than 40°. To launch visible lights into the structure, silica fiber tapers (a and b) were used to couple visible lights by evanescent wave coupling (Figure 1b). Figure 1c−f shows optical microscope images of the mixed colors. In Figure 1c, a mixed yellowish-green spot (inset of Figure 1c) was observed at the crossed junction with a spot radius of 301 nm and a color coordinate in the Commission International de l'Eclairage (CIE) chromaticity diagram of $(x, y) = (0.27, 0.70)$ (see Supporting Information, Figure S1), which was formed by launching a power ratio of about 6:10 of red (650 nm) and green (532 nm) lights into nanofibers 1 and 2, respectively. The light sources used are laser diode for red light and diode pumped solid-state (DPSS) laser for green light. Both the maximum output powers are 10 mW. The transmitted powers of the red and green lights in nanofibers 1 and 2 are 10.0 and 16.7 μW (*i.e.*, total power is 26.7 μW), which were coupled through the silica fiber tapers (a and b), respectively. The coupling efficiency of the red light from the silica fiber taper a to the PTT nanofiber 1 is about 95%, while coupling efficiency of the green light from the silica fiber taper b to the PTT nanofiber 2 is about 93%. In this structure, the crossed junction acts as an optical scattering center. Therefore, both the red and green lights were scattered by the scattering center. The scattered red and green lights were mixed at the junction. As a result, a yellowish-green spot was formed. The color of the spot at the crossed junction can be easily tuned by changing the total power and the power ratio of the launched red and green lights. For example, if the power ratio of the red and green lights was changed to be red/green = 26:9 (total power, 52.6 μW), a mixed color of greenish-yellow can be observed (inset of Figure 1d). When the power ratio of red/green = 27:4 (total power, 47.6 μW), the color is orange (inset of Figure 1e). Similarly, a reddish-orange (inset of Figure 1f) color is obtained at a power ratio of red/green =32:2 (total power, 48.7 μW). For a fixed size of crossed junction (*i.e.*, fixed scattering center), the scattered optical spot is a little different for different power ratios of the red and the green lights. The radii of the spots are 303, 306, and 310 nm for Figure 1

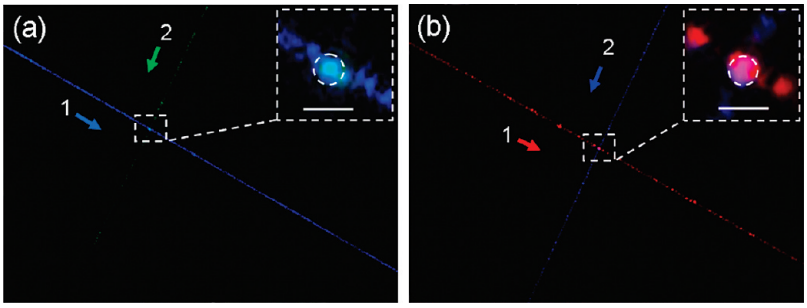


**Figure 2. Optical microscope images of the mixed colors at the junction of the structure. The insets show zoomed (×10) views of the spots at the crossed junctions. The arrows show the propagation directions of the lights. Scale bars in the insets of panels a and b are 10 μm.**

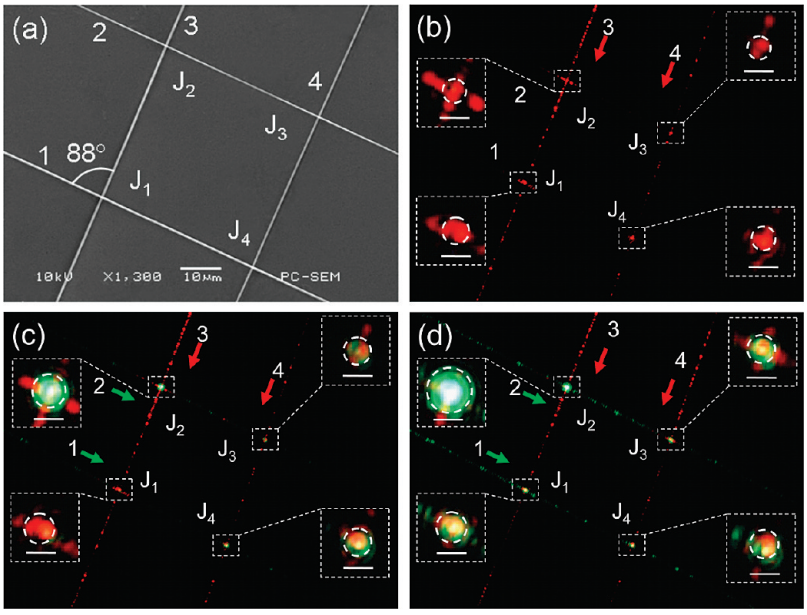


**Figure 3. The 2 × 2 crossed structure. (a) SEM image of the structure with diameter of 606, 546, 682, and 614 nm for the nanofibers 1, 2, 3 and 4, respectively. (b−d) Optical microscope images of the guided visible lights in the structure. The insets show magnified (×5) views of the spots at the corresponding crossed junctions. Scale bars in the insets of panels b−d are 10 μm. The arrows show the propagation directions of the launched lights.**

panels d, e, and f, respectively. The respective color coordinates in the CIE chromaticity diagram are (0.45, 0.54), (0.56, 0.43), and (0.64, 0.35) for Figure 1 panels d, e, and f (see Supporting Information, Figure S1).

A similar phenomenon was also observed by launching blue and green lights into the nanofibers 1 and 2, respectively. The blue light source used is also DPSS laser with the maximum output power of 10 mW at a wavelength of 473 nm. Figure 2a shows a blue-green spot formed at the crossed junction by launching a power ratio of about 19:9 of blue and green lights in the nanofibers 1 and 2 (total power, 31.2 μW), respectively. The blue-green spot radius is 302 nm (inset of Figure 2a) and the color coordinate is (0.13, 0.27). If there was launched a power ratio of about 20:5 of red and blue lights in nanofibers 1 and 2, respectively, with a total power of 71.3 μW, a purplish-red spot could be obtained at the crossed junction with a spot radius of 284 nm (inset of Figure 2b) and a color coordinate of (0.52, 0.21). Similarly, the color of the spot at the crossed junction can be easily tuned by changing the power ratios of the launched blue and green lights, or red and blue lights (see Supporting Information, Figures S2 and S3). The demonstration shows that, by changing the power ratios of the launched red, green, or blue lights, a desired color can be obtained at the crossed junctions of the nanofibers. Moreover, the color coordinates of these spots at the crossed junction lie far outside the current National Television System Committee standard color triangle, which indicates our nanodisplay would provide a significantly larger color triangle on the CIE chromaticity diagram (see Supporting Information, Figure S4).

Figure 3a shows a 2 × 2 crossed structure which was assembled by nanofibers 1, 2, 3, and 4 with diameters of 606, 546, 682, and 614 nm, respectively (see Methods for details). The average distance between nanofibers 1 and 2 or 3 and 4 is about 41 μm. In this experimental demonstration, nanofibers 1 and 2 are for

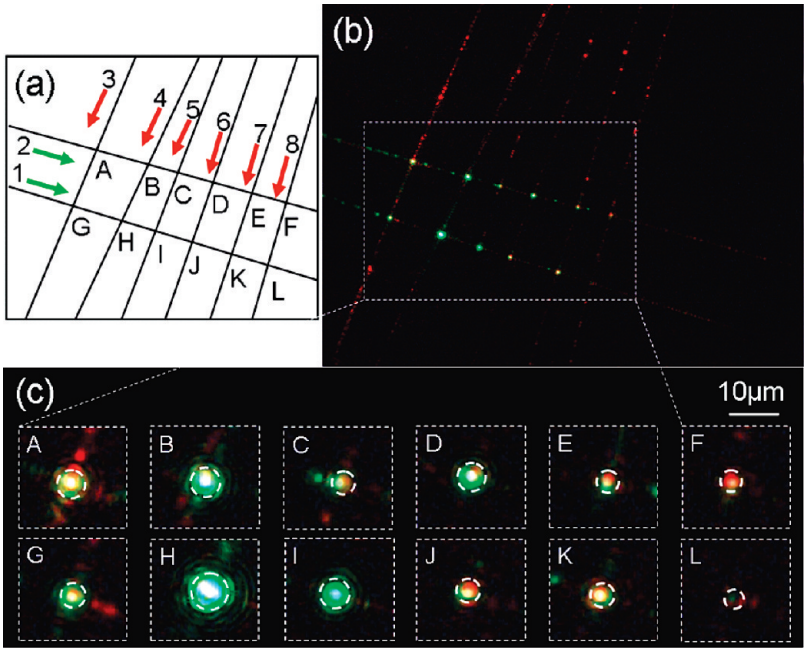


**Figure 4. The 2 × 6 crossed nanofiber array structure. (a) Schematic diagram of the structure. The arrows show the propagation directions of the launched lights. (b) Optical microscope image of the mixed colors in the structure. (c) Magnified (×5) view of the spots at the crossed junctions from A to L.**

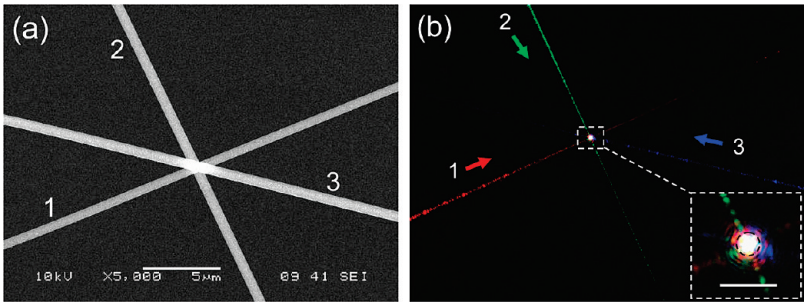


**Figure 5. The 3 × 3 crossed structure. (a) SEM image of the device with diameter of 558, 598, and 598 nm for the nanofibers 1, 2, and 3, respectively. Nanofiber 1 is perpendicular to nanofiber 3, the cross-angle of nanofibers 2 and 3 is about 50°. (b) Optical microscope image of the guided visible lights in the structure. The inset shows a magnified (×5) view of the white spot at the crossed junction. The arrows show the propagation directions of the launched lights. Scale bar in the inset is 20 μm.**

green light transmission while nanofibers 3 and 4 are for red light transmission: (1) The red light with a total power of 102.6 μW and a power ratio of about 63:52 was launched into nanofibers 3 and 4, but without green light in the nanofibers 1 and 2, the colors of the spots at the crossed junctions $J_1$−$J_4$ are red (Figure 3b). The corresponding color coordinate is (0.72, 0.28). The spot radii are 896, 791, 774, and 800 nm at the junctions $J_1$, $J_2$, $J_3$, and $J_4$, respectively. The largest spot is $J_1$ while the minimum one is $J_3$. The main reason is because the sizes of the scattering centers (*i.e.*, junctions) are $J_1 > J_2 > J_4 > J_3$. (2) The total power and the power ratio of the red light in nanofibers 3 and 4 remain unchanged and the green light was launched with a total power of 14.3 μW and a power ratio of 7:9 into nanofibers 1 and 2, as shown in Figure 3c; the colors of the spots were changed to reddish-orange, yellowish-orange, orange, and orange at the junctions $J_1$, $J_2$, $J_3$, and $J_4$, respectively. The corresponding color coordinates are (0.60, 0.39), (0.55, 0.43), (0.57, 0.42), and (0.56, 0.44) while the spot radii are 1009, 1113, 913, and 922 nm at the junctions $J_1$, $J_2$, $J_3$, and $J_4$, respectively. (3) With a further increase of the power of the green light, different spot colors can be obtained. For example, when the power of the green light was increased to 25.0 μW with a ratio of 13:15 at nanofibers 1 and 2, the spot colors at junctions $J_1$, $J_2$, $J_3$, and $J_4$ were changed to yellowish-orange, yellow, yellowish-orange, and yellowish-orange, respectively, as shown in Figure 3d. The corresponding radii of the spots are 1017, 1513, 930, and 957 nm, while the corresponding color coordinates are (0.51, 0.47), (0.50, 0.48), (0.52, 0.47), and (0.52, 0.48). It should be pointed out that the color at the center of the spot of the $J_2$ looks white. This was caused by display error of the CCD due to the relatively large optical power of the green light. By comparing Figure 3 panel d with panel c, it can be seen

that, with an increase of the power ratio of the green lights, the spot sizes at the corresponding crossed junctions become larger. This is due to stronger scattering occurring for higher power of the green light. This indicates that four colorful spots can be obtained by the nanofiber-based 2 × 2 crossed array. By using different diameters of nanofibers and launching red, green, and blue lights, different spot sizes and color spots can be obtained. Furthermore, the size and the color of the spots can be tuned by changing the power ratios of the launched RGB lights. Therefore, the desired 2 × 2 color array for display with tunable ability can be obtained.

Furthermore, we have also assembled a 2 × 6 crossed nanofiber array structure as schematically shown in Figure 4a. Figure 4b shows the optical microscope image with a total power of 21.9 $\mu$W green lights transmitted in nanofibers 1 and 2 (power ratio, 19:20) and a total power of 164.8 $\mu$W red light in nanofibers 3−8 (power ratio, 72:43: 39:40: 49:50). The diameters of nanofibers 1−8 in Figure 4b are 622, 638, 734, 765, 574, 613, 629, and 670 nm. From Figure 4b, it can be seen that, a colorful display was obtained. Figure 4c shows enlarged spot colors for each crossed junctions. Since the diameters of the nanofibers and the transmitted optical powers in each nanofiber are different, so the spot sizes and the colors are different. As shown in Figure 4c, the mixed colors at junctions A−L are yellowish-orange, yellowish-green, yellow-green, yellow-green, reddish-orange, reddish-orange, yellow-green, yellowish-green, yellowish-green, yellowish-orange, orange, and reddish-orange. The corresponding color coordinates are (0.51, 0.48), (0.37, 0.60), (0.40, 0.58), (0.45, 0.54), (0.59, 0.39), (0.61, 0.38), (0.45, 0.53), (0.36, 0.61), (0.36, 0.62), (0.51, 0.49), (0.58, 0.41), and (0.60, 0.39). The corresponding radii of the spots at the junctions from A to L are 560, 585, 459, 566, 446, 428, 491, 729, 591, 472, 478, and 384 nm. In application, if the launched power ratio is changed, particularly, if there is a change in the power ratio launched into nanofibers 1 and/or 2, the colors of the array can be easily changed.

White color can also be obtained by simply assembling the nanofibers and launching the RGB lights into them. For example, we assembled a 3 × 3 structure (Figure 5a) using nanofibers 1, 2, and 3 with diameters of 558, 598, and 598 nm, respectively, and launched RGB lights into nanofibers 1, 2, and 3, respectively, with a total power of 63.4 $\mu$W and a power ratio of about 50:13:10. A white color at the center of the spot with a radius of about 818 nm was observed at the crossed junction (inset of Figure 5b). The color coordinate was (0.41, 0.35). Its correlated color temperature (CCT) is 3026 K. About 80% power of the RGB lights were mixed at the junction, therefore an estimated luminous efficiency for this case is about 134 lm $W^{-1}$, which is higher than those of the electrically driven displays (0.1 lm $W^{-1}$ for quantum dot and polymer composites,[18] 1.5−2.0 lm $W^{-1}$ for molecules and polymer,[19] and 1.46−4.17 lm $W^{-1}$ for single-polymer[20]). It should be pointed out that, at around the white color of the spot center, red-green-blue mixed color occurred. This was due to the radii of the scattered RGB spots at the junction being different. For different power ratios of the RGB lights, the color coordinates and the CCT of the generated white spot at the junction will be different (see Supporting Information, Figure S5). By using suitable diameter of the nanofibers or by tuning the power ratio of the launched RGB lights, a pure white color spot can be achieved. The experiment demonstrates that the color coordinates can be tuned from (0.26, 0.25) to (0.42, 0.36) across the CIE chromaticity diagram along with their corresponding CCT tuned from 21883 to 2915 K (see Supporting Information, Figure S5). The result exceeds LED standard and is comparable to the reported white LEDs.[21] By assembling more nanofibers and if a logic optical circuit is designed and applied to control the input power ratios, tunable all-optical full-color displays can be achieved.

In conclusion, a series of crossed nanofiber structures for nanodisplay were assembled. The performance of the crossed structure depends mainly on the combination of inputted power ratios of RGB lights and dimensions of the crossed junctions. For a fixed structure (*i.e.*, fixed diameters of nanofibers), a desired display size and color can be obtained by controlling the total power and power ratios launched into the nanofibers. This experiment demonstrates that, by using this method, a large-scale colorful nanodisplay can be achieved with all colors ranging from red to violet while avoiding the use of color filters and complicated photolithography processing. It also presents a method to develop white light illumination by the combination of RGB lights. These will be useful in future miniaturized displays and white light illumination with higher efficiency compared with the efficiencies of the electrically driven displays.

## METHODS

In the assembly of a 2×2 crossed array, first, two as-fabricated PTT nanofibers were placed on a cleaned glass (index, 1.50) substrate along the horizontal direction under a microscope. Each end of the nanofiber was fixed by a microstage. By adjusting the microstages, two paralleled nanofibers can be formed. Second, another two paralleled nanofibers were placed on them using the same method to form a 2 × 2 crossed array. Finally, four tapered silica fibers with diameters of approximately 600−900 nm were used for light launching. In the experiment, the tapered silica fibers-linked red (650 nm), green (532 nm), and blue (473 nm) lights were fixed on three manual 6-axis units to contact crossed nanofibers through van der Waals force. Optical microscope images were recorded with a three-dimension measuring microscope. The optical powers were measured by an optical spectrum analyzer and an optical power meter.

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*Supporting Information Available:* CIE chromaticity of the spots, optical microscope images of the mixed colors at the junction, CIE color coordinates of spots at the junctions, output and scattering efficiency dependence on nanofiber diameter and cross angle, flexibility demonstration of the devices. This material is available free of charge *via* the Internet at http://pubs.acs.org.

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