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Spatial mode rotator based on mechanically induced twist and bending in few-mode fibers

Dawei Yu[a], Songnian Fu*[a], Ming Tang[a], Perry Shum[b], and Deming Liu[a]
[a] National Engineecoil Laboratory for Next Generation Internet Access System, School of Optics and Electronic Information, Huazhong University of Science and Technology, Wuhan, China, 430074;
[b] Photonics Centre of Excellence, Nanyang Technological University, Singapore 637553

ABSTRACT

Recently, few-mode fiber (FMF) based mode division multiplexing (MDM) transmission together with multi-input multi-output (MIMO) signal processing technique is ideal candidate to solve future single mode fiber (SMF) capacity crunch. Most existing mode division multiplexers/demultiplexers (MMUX/DEMMUX) have a specific mode orientation for high-order non-circular symmetric mode. Taking the phase plate based DEMMUX as example and converting LP_{11} mode to fundamental LP_{01} mode, we need optimize input mode orientation the same as the phase pattern of phase plate. In this submission, we propose and experimentally demonstrate a spatial mode rotator based on mechanically induced twisting and bending in a step-index FMF. We theoretically find that the mode coupling strength between vector modes with similar propagation constants is determined by the FMF bending and twisting. When the input LP_{11} mode cluster including TE_{01}, HE_{21a}, HE_{21b}, and TM_{01} mode are properly perturbed, the output optical field is superposed as LP_{11} mode with a rotation. Therefore, the proposed spatial mode rotator is composed of three FMF coils with a radius of 16 mm, while the number of each coil is 2, 1, and 2, respectively. Consequently, we are able to rotate the LP_{11} mode with arbitrary angle within 360º range using the same conventional configuration of polarization controller (PC). The insertion loss of proposed spatial mode rotator is less than 0.82 dB, when the operation wavelength varies from 1540 nm to 1560nm. In particular, from the measured mode profile, there exists little crosstalk between LP_{01} mode and LP_{11} mode during mode rotation operation.

Keywords: spatial mode rotator, few-mode fiber, optical fiber, mode division multiplexing, fiber bending, fiber twisting, optical fiber communication

1. INTRODUCTION

Recently, few-mode fiber (FMF) based mode division multiplexing (MDM) transmission together with multi-input multi-output (MIMO) signal processing technique is a strong candidate to enhance fiber-optical transmission capacity and avoid the coming single mode fiber (SMF) capacity crunch[1,2]. Different from the traditional multi-mode fiber (MMF), FMF can only support several propagation modes, whose number is much less than that of the MMF. Determined by the geometry structure parameters and refractive index, the inter-mode dispersion is much smaller, making it possible to carry modulated signals as independent channel for individual modes. The practical propagation modes used as the information channels are the well-known linearly polarized (LP) modes. Actuarially, the LP modes in FMF which are used as the multiplexed channels can be divided into two types according to the spatial symmetry characteristics, i.e., circular symmetric modes and non-circular symmetric modes[3]. For example, the LP_{0m} mode is circular symmetric mode, the electric field distribution along the angular direction is continuous and the amplitude is same for the circle line of the same radius. Whereas the $LP_{l,m}$ ($l > 0$) mode is non-circular symmetric mode, the electric field distribution along the angular direction is cut into several segmentations. Most of the reported mode division multiplexers/demultiplexers (MMUX/DEMMUX) which can combine/separate the multiplexing mode channels have one special mode orientation for the non-circular symmetric modes[2,4,5]. For example, the phase plate based MMUX/DEMMUX is fixed to deal with the LP_{11} mode with specially designed orientation[2].

The orientation of propagation mode maintains the primary state along the fiber under ideal conditions. However, it is not the case in practical situations due to the weak or strong perturbation of the FMF. Taking the weak perturbation as an example, the orientation of the propagation mode will change randomly as the light propagates forward because the fiber

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is induced small twist and stress in practical application. The ratios of the waveguide modes which compose the corresponding LP mode change with the perturbation of the FMF, resulting in the orientation variation. This makes it difficult to convert the high order mode back to the fundamental mode and separate the multiplexed mode channels through the DEMMUX. It stems from the fact that the mode demultiplexing process is usually the inversed case of the multiplexing one. Taking the phase plate based MMUX/DEMMUX as an example, if we want to convert the LP_{11a} mode to the fundamental mode (LP_{01} mode), the mode orientation is required to be the same with the phase mask on the phase plate. If not, the insertion loss will increase, or even worse, the conversion process can be failed. Since the mode coupling always occurs due to the perturbation of the FMF, the mode orientation in the FMF usually evolves randomly. Thus, it is hard to set the output mode orientation the same as that of DEMMUX. Until now, orientation rotation of LP_{11} mode has been realized in the PLC-based waveguide[7]. However, the rotation angle is fixed according to the length of waveguide.

In this submission, we first show the structure of our designed FMF and discuss the properties. Then stimulated by the operation function of conventional polarization control (PC), we investigate the effect of twist and bend of the FMF on the mode orientation rotation. Through changing the twist angle, bending radius and bending coil numbers, we study the influence strength of fiber twisting, bending radius, and coil numbers on the mode coupling strength between the fiber modes whose propagation constants are very close. Next the mode orientation rotation effect with respect to the fiber twisting, bending radius and coil numbers is experimentally investigated. Finally, we realize the mode orientation rotation with arbitrary angle mechanically by optimizing the bending radius, coil numbers.

2. DESIGN AND CHARACTERISTICS OF FMF

The FMF which can be used in the MDM system are usually the step-index profile and graded-index (GRIN) profile. The FMF fabricated by our group is the four-mode weakly-coupled FMF with a step-index profile core[6]. In order to balance the mode coupling and the large effective area at the operation wavelength of 1.55μm, we choose the core radius, refractive index of core and cladding to be 9.5μm, 1.4615 and 1.45601, respectively. After fabrication, the refractive index distribution and cross-sectional view are shown in Fig. 1. The degenerate modes have similar propagation constants, for example the LP_{11a} and LP_{11b}, LP_{21a} and LP_{21b}. Large effective area and large differential mode group delay (DMGD) can be guaranteed.

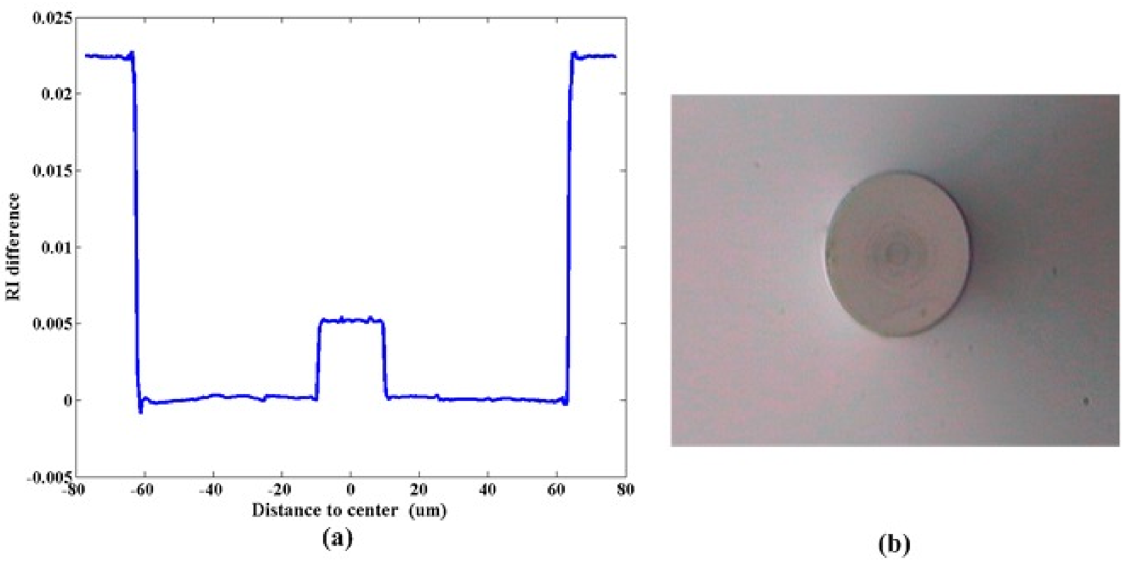


Fig. 1. Characterization results of the fabricated FMF. (a) shows the refractive index profile; (b) is the cross-sectional view.

3. ROTATOR SETUP AND OPERATION PRINCIPLE

When the fiber is bent, the local permittivity is disturbed and mode coupling occurs between the vector modes whose propagation constants are close. If we wrap the FMF, as shown in Fig. 2 (a), the mode coupling along the fiber in the ring is linear. The lateral, compressive stress $-\sigma_x$, that builds up in a bent fiber under the conditions of "large" deformations modifies the refractive index of the FMF material. The stress is determined by the curvature κ ($\kappa = 1/R$) and Young's modulus E [8].

$$\sigma_x(x) = \kappa^2 (E/2)(x^2 - r^2) \tag{1}$$

where r is the radius of the FMF. This stress mainly results in the mode coupling between the orthogonal polarized vector modes with the same propagation constants.

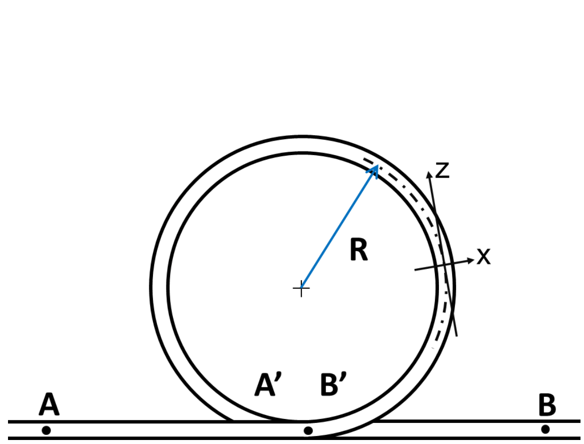
The influence of twist is intimately related to the influence of the linear birefringence that exists in optical fiber, due to the fact that its core deviates from a circular shape or due to internal stress[9], as shown in Fig. 2 (b). The evolution of the fields along the fiber can be described by a set of coupled-mode equations. The imperfections in FMF like twist-induced shear stress or a deformation of the core may increase the coupling strength between the vector modes whose propagation constants are very close. The effect is the re-distribution of the optical field in the FMF. The fields in the imperfect FMF are described in the superposition of the modes of the ideal FMF. The transverse field distribution in the imperfect FMF can be expressed as

$$E^t(x, y, \mathrm{z}) = \sum_m A_m(z) E_m^t(x, y) = \sum_m a_m(z) E_m^t(x, y) \exp(ik_m z), \tag{2}$$

where $E_m^t(x, y)$ is the transverse field distributions of the ideal FMF, m is the mode number, k_m is the wave number of mode m, and $a_m(z)$ is the amplitude of mode at a given plane z. After derivation, the wave equation in the perturbed FMF reduces to a set of coupled-mode equations for the $a_m(z)$,

$$\frac{da_m(z)}{dz} = i\sum \kappa_{mn} a_n(z) \exp\left[i(k_n - k_m)z\right], \tag{3}$$

where k_{mn} is the coupling coefficients which depends on the perturbation of permittivity induced by the fiber twist and bend. This equation predicts the potential of changing the mode coupling effect through controlling the FMF twist and bend. We know that LP_{11} mode is composed of TE_{01}, TM_{01}, HE_{21a}, and HE_{21b} modes. If the amplitude of TE_{01} and HE_{21a} maintains the same value after perturbation, while that of TM_{01} and HE_{21b} is another value, the superposition field is still LP_{11} mode, but the orientation differs from the LP_{11a} or LP_{11b}. The ratios of each waveguide modes are determined by Eq. (2).



(a) (b)

Fig. 2 Schematic diagram of FMF bending and twisting. (a) Bending FMF. (b) Coordinate systems of twisted FMF.

Fiber bending and twisting are the easiest operation which affects the mode coupling and mode distribution in the FMF. We are able utilize such effect to realize controllable mode coupling coefficients variation in order to rotate the orientation of LP_{11} mode with expected angles. We can coil the FMF into a set of coils with a finite radius. The bending induced by the coils will generate determined mode coupling effect. However, the mode coupling effect of the fiber twisting can be controlled by the rotation of the fiber coils. Large twisting helps to strengthen the deformation of the fiber core and contributes to the mode orientation variation.

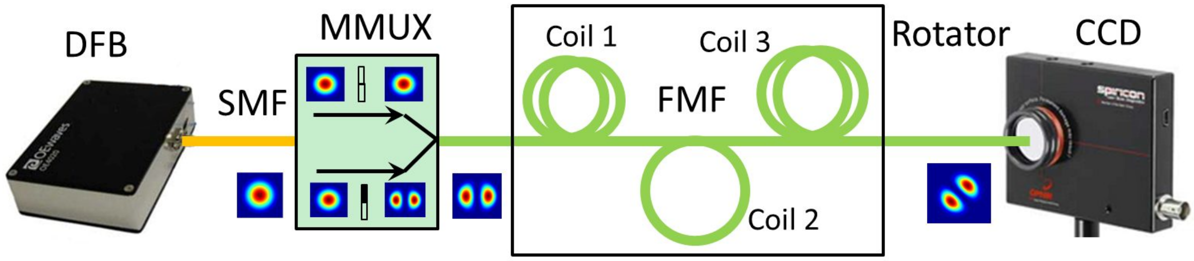


Fig. 3. Mode rotation experimental setup. DFB: distributed feedback laser diode; MMUX: mode multiplexer based on LCOS; CCD: Infrared CCD camera.

The experiment setup to realize mode orientation rotation is shown in Fig. 3. The laser source is a wavelength tunable distributed feedback (DFB) laser diode (LD). The mode multiplexer based on liquid crystal on silicon (LCOS) can realize the mode selective excitation in FMF. The 4-mode FMF under test is designed by our group as described previous. An infrared CCD camera can capture the optical field distribution out of the FMF. The rotator is the set of fiber coils as depicted in the black pane. Through the optimization of the coils, we can obtain good LP_{11} mode rotator.

4. EXPERIMENT RESULTS AND DISCUSSION

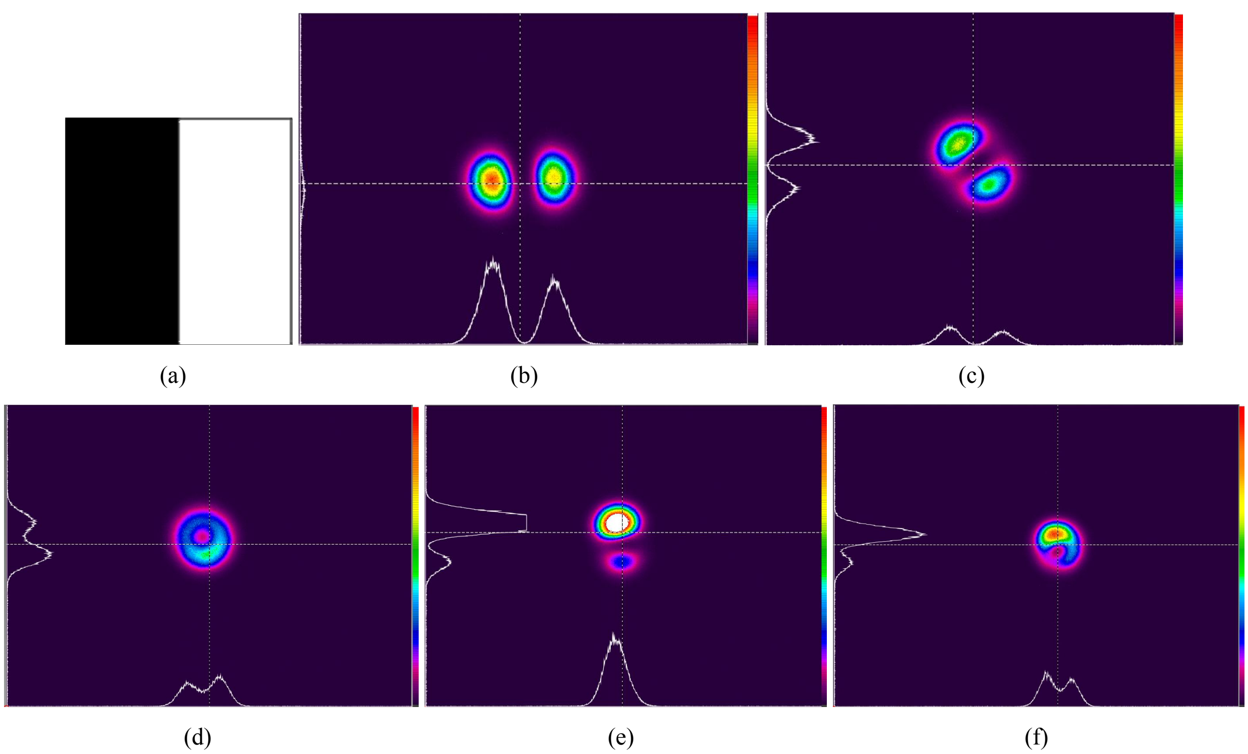
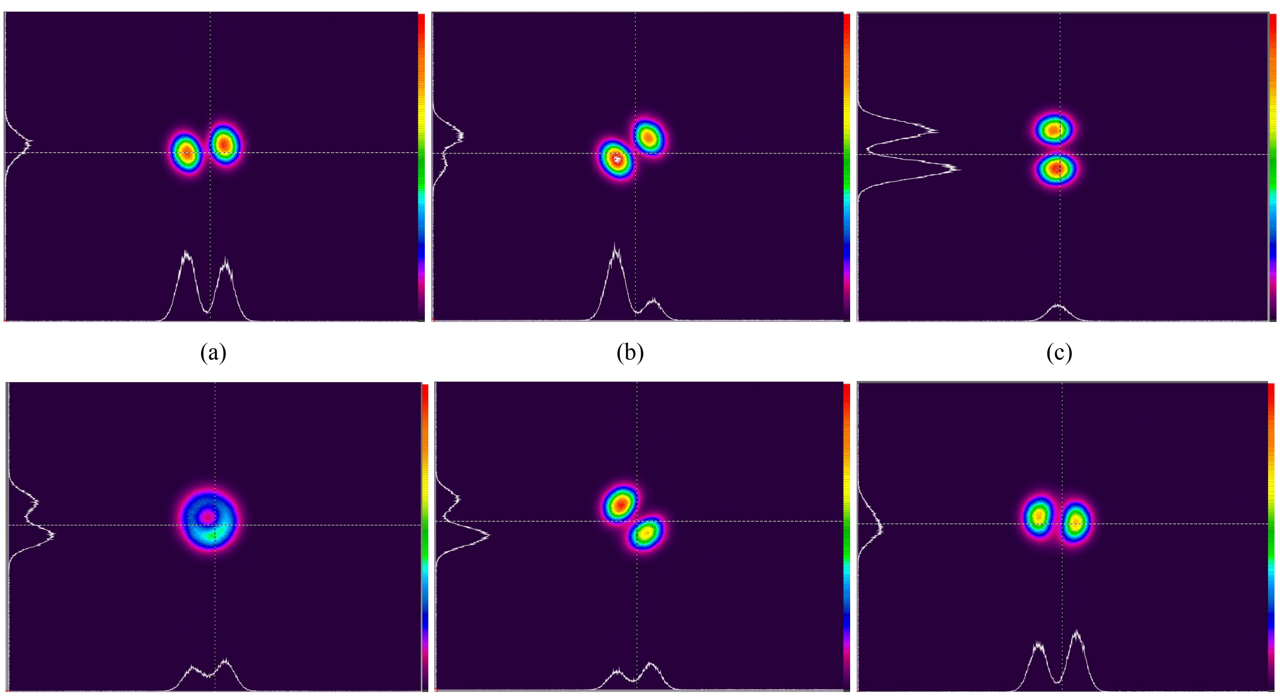


Fig. 4. Field distribution of LP_{11} mode after 2m FMF. (a) Phase mask for LP_{11} mode conversion. (b) No perturbation. (c) Small stressing. (d), (e) represent the situation of sever bending. (f) represent the situation of strong twisting.

When the phase mask loaded on the LCOS takes the form of Fig. 4 (a), we can selective excite the LP_{11} mode at the FMF input. After 2 m FMF, the far field distribution is shown as Fig. 4 (b). If we add some perturbation on the FMF, such as stress, bend, or twist, the optical field in the FMF will change. Fig. 4 (c), (d), (e), and (f) show some optical field distributions with fiber perturbation. Obviously, the field distribution is no longer a pure LP_{11} mode after disturbed by the strong fiber bending or twisting. It indicates that the combination of bending and twisting is necessary to realize mode orientation rotation, different from the case of polarization control.

If we bend the FMF into a few planar coils and rotate them, the mode state in the FMF changes correspondingly. Through analyzing the captured optical field distribution, we can get knowledge of how the mode coupling occurs between the modes. By changing the numbers, radius, and rotation of the coils, interesting mode coupling results can be obtained. When only LP_{01} mode propagates in the FMF, the captured optical field distribution almost keeps invariant no matter how the fiber coils change. This is because the LP_{01} mode is composed of two degenerated modes whose polarizations are orthogonal, i.e. HE_{11x} and HE_{11y}. When the FMF are perturbed through coiling, only the coupling between the two modes takes place, and no intensity distribution changes, just like the case of SMF. However, the optical field distribution changes quickly with the coils when LP_{11} mode propagates in the FMF. When we decrease the coil radius, the mode coupling effect becomes more sensitive to the rotation of the coils. Small rotation will result in severe optical field distribution variation. This is because the twist-induced stress becomes stronger when the coil radius is small. Thus the mode coupling strength rises.

It is very interesting that the profile of the LP_{11} mode almost keeps the same but the orientation changes when the coil is rotated to certain states. If we use only one set of coils, e.g. "Coil 1" in Fig. 3, we can realize the LP_{11} mode orientation rotation only when the coils are rotated to some certain states and the rotation angle are some fixed values as shown in Fig. 5 (a), (b), and (c). The profile of the mode after rotated changes little, indicating of high purity of LP_{11} mode. But it is this case only when the coil planes are rotated to some certain states. In other states, complex mode coupling occurs, as shown in Fig. 5 (d). The intensity in the center of the spot is always very small, indicating that the coupling of HE_{11} mode is rarely small. We can believe that the coupling between TE_{01}, TM_{01}, EH_{21a}, and EH_{21b} dominants the mode coupling process when rotating the fiber coils. This makes it possible to rotate the orientation of LP_{11} mode without increasing the mode crosstalk between LP_{11} and LP_{01} mode when the two modes are multiplexed in MDM transmission system. If we increase the number of coils, however, the mode rotation effect becomes more obvious. Continuous mode rotation can be realized in an angle region of 65°when we rotate the coil plane within a certain angle region.



(a) (b) (c)

(d) (e) (f)

Fig. 5. Captured optical field distribution. The four pictures represent the LP_{11} mode far field distribution after the fiber coils.

Since one set of coils can realize the mode rotation of 65º, it is possible to rotate the mode within 360º using three set of coils. When we coil the FMF into three set of coils with a radius of 32 mm, and the number of coils are 2, 1, and 2, respectively, we can rotate the mode orientation with any angle through rotating these coils, just like the operation of the mechanical polarization controller. Fig. 5 (e) and (f) show the mode orientation of other rotation angles. Obviously, though not all the states of the coils can maintain the perfect LP_{11} mode, any orientation rotation angle can be realized by rotating the three set of coils. This scheme has the advantage of tunable rotation angle compared with the PLC-based rotator. Further investigations show that the insertion loss induced by the fiber coils is less than 0.5dB when we rotated the coils. When we change the working wavelength, the effect of mode rotation changes a little. The coils states vary with working wavelength when we get the same mode rotation angle. However, mode rotation within 180ºcan always be realized when the wavelength varies from 1540 nm to 1560nm, and the insertion loss maintains lower than 0.8 dB. Thus the proposed configuration can be used to rotate the spatial mode orientation that is needed in the mode demultiplexing process.

5. CONCLUSIONS

In conclusion, we analyze the influence of bending and twisting of FMF on the mode coupling and mode orientation rotation. Fiber bending and twisting can cause the coupling between the waveguide modes with similar propagation constants. Small coil radius and strong twist increase the mode coupling strength. The proposed spatial mode rotator is composed of three FMF coils with a radius of 16 mm, while the number of each coil is 2, 1, and 2, respectively. Consequently, we are able to rotate the LP_{11} mode with arbitrary angle within 360º range using the same configuration of conventional polarization controller (PC). The insertion loss of proposed spatial mode rotator is less than 0.82 dB when the operation wavelength varies from 1540 nm to 1560nm. In particular, from the measured mode profile, there exists little crosstalk between LP_{01} mode and LP_{11} mode during mode rotation operation.

6. ACKNOWLEDGEMENT

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