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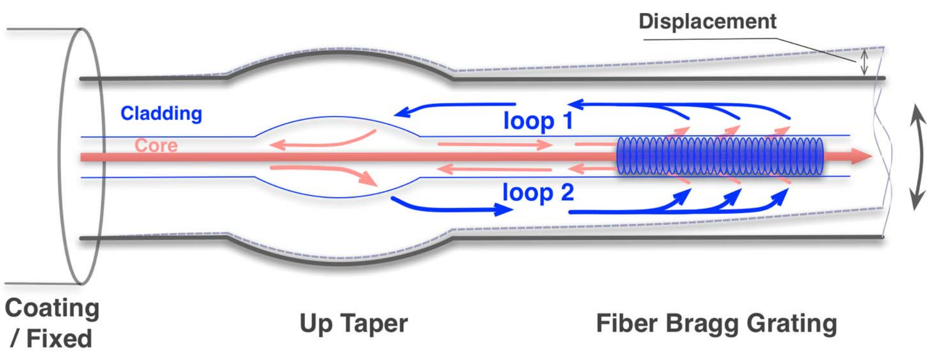

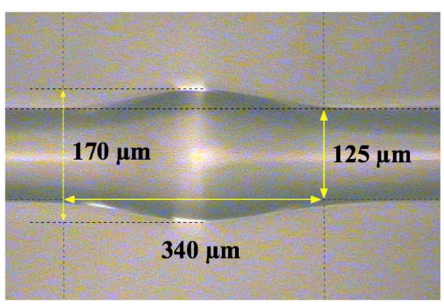

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Abstract: A temperature-insensitive fiber-optic displacement sensing scheme by cascading the fiber up taper and Bragg grating is experimentally demonstrated. The strength-robust up taper, which is fabricated by excessively splicing the Bragg grating to the interrogation fiber, functions as the bridge between the core mode and the cladding modes. This cascading structure realizes the cladding-mode backward recoupling, and displacement information can be directly read out by measuring the power of the highly bending sensitive recoupled cladding modes. Two sensing configurations that respectively utilize the normal fiber Bragg grating (FBG) and the uniform chirped FBG (CFBG) for the cladding-mode backward recoupling have been studied contrastively, in which the tunability of the up taper is fully validated to support a better dynamic range of the measurement. Aiming to improve the low reflection power and enhance the sensing sensitivity, the CFBG is used, and the reflection power is increased by more than 200 times and reaches 176 μW, which lowers the precision requirement for the optical power meter and potentially reduces the cost of the sensing system.

Index Terms: Fiber up taper, fiber Bragg grating, displacement sensor, temperature-independent.

1. Introduction

Micro-displacement measurement has always been the focus in traditional sensing area. Optical fiber sensor, by virtue of its passive operation and immunity to electro-magnetic interference, opens up plentiful opportunities for displacement sensing applications in hard-to-reach circumstances. From the intuitive bending induced attenuation [1] to the sophisticated but highly sensitive fiber birefringence based interferometer [2], displacement information can be interrogated through the power change or the wavelength shift. Fiber Bragg grating (FBG), as one of the most widely used fiber sensor devices, also provides the displacement measurement solutions either by using an edge filter to interrogate the resonant wavelength [3] or a cantilever to transfer the displacement into the chirp profile of the FBG [4]. In these sensing schemes, peripheral components like edge filter or mechanical cantilever are needed, which complicates the sensing systems. Moreover, temperature cross-sensitivity is another problem that must be taken into consideration especially in the wavelength-interrogation paradigm.

Recently, optical fiber sensor based on the cladding-mode backward recoupling has drawn intense attention [5]–[9]. Compared to the fundamental core mode, optical fiber cladding mode shows much higher sensitivity to micro deformations like structural bending [10]. The usually dismissed or even undesirable mode coupling capability between the core mode and counter-propagating cladding modes of the FBG occupies an important role in this kind of sensor [11]. The tilted FBG (TFBG), as one of the derivatives of the normal Bragg gratings, is also utilized for its high core-cladding mode coupling efficiency owning to the slightly slanted grating plane [5]. By incorporating a mode coupling structure that functions as the bridge between the core mode and the cladding modes upstream from the Bragg grating, the cladding modes that should be dissipated in transmission can now be interrogated by either an optical power meter (OPM) or an optical spectrum analyzer. In both interrogation methods, temperature induced cross-sensitivity can be well eliminated or compensated. Fiber-optic sensor based on the cladding-mode backward recoupling owns the advantages of structural simplicity, reflective operation and controllable cross-sensitivity.

In this study, we propose and demonstrate a temperature insensitive all-fiber displacement measurement scheme by excessively splicing the Bragg grating to the interrogation fiber. The excessive splice induced fiber up taper, which is firstly introduced in the fiber interferometer [12] and modified in our sensor, together with the Bragg grating forms a cladding-mode backward recoupling structure. Contrary to the regular biconical taper manufactured by heating and pulling [5], the up taper used for the mode conversion is a waist-enlarged and strength-robust fiber structure. Meanwhile, the length of the up taper is less than 500 μm which ensures the compactness of the sensor while eliminating the use of special fiber [7], [8]. Transverse displacement loaded at the end of sensor can be directly read out through the reflected cladding mode power. Two sensing configurations that respectively utilize a normal FBG and a uniform chirped FBG (CFBG) for the cladding-mode backward recoupling are studied contrastively in the displacement measurement. The cladding mode and core mode power responses to the displacement are studied in the FBG configuration. Aiming to improve the low reflection power, the CFBG is used instead, which provides a distinct boost in the reflection power. The maximum reflection power is increased from 800 nW to 176 μW, which helps to reduce the precision requirement for the OPM. The dynamic range of the sensing structure is also guaranteed by appropriately tuning the fusion parameter of the up taper. Meanwhile, owning to the symmetry of the up taper and the Bragg grating in our sensor, the responses of the cladding mode to the displacement show little direction dependency which should be avoided in structure sensing applications [9]. Therefore, no calibration is needed to achieve maximum sensitivity. Temperature characteristic to both sensing configurations is studied, and the temperature induced fluctuation of the reflection power is well controlled.

2. Sensor Structure and Fabrication

The structure for cladding-mode backward recoupling is realized by concatenating the up taper and the Bragg grating (see Fig. 1, here we use the normal FBG as an example, this mode coupling principle can be also applied to other Bragg gratings, like CFBG). The sensing structure based on the mechanism of cladding-mode backward recoupling consists of two key components: the fiber up taper and the FBG or its derivatives. The up taper is used for mode coupling between co-propagating modes, while the Bragg grating is used for wavelength-selective mode coupling between counter-propagating modes. The sensing structure is illuminated by a broad-band source (BBS) from the interrogation fiber. At the up taper, the core mode experiences certain loss, while the cladding modes are excited. Cladding modes then travel to the fiber grating without much attenuation as the fiber coating is removed and the sensor is strictly kept straight. According to [11], two types of mode coupling mechanism take place when core mode and cladding modes encounter the fiber grating: a) the guided core mode is coupled to the backward-propagating cladding modes by the grating, then the cladding modes are recoupled to the guided core mode at the up taper. We call this energy coupling path loop 1; b) the cladding modes excited at the up taper are recoupled to the guided core mode by the fiber grating and finally get into the interrogation fiber, which completes the loop 2. Actually, there also exists mode coupling between counter-propagating cladding modes

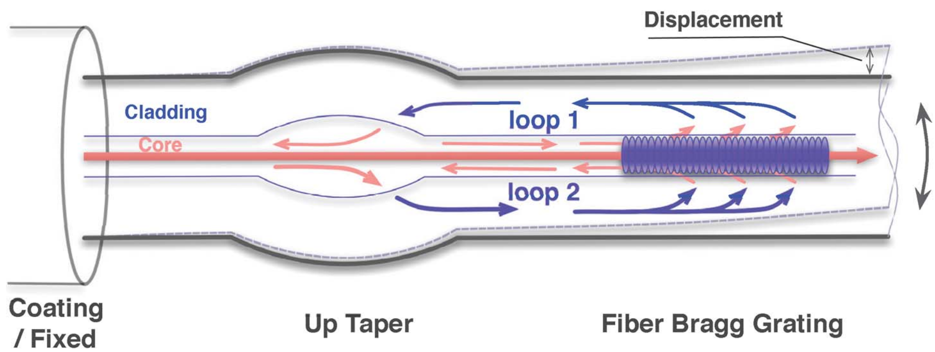

Fig. 1. Schematic diagram of the proposed cladding-mode backward recoupling structure incorporating the up taper and the fiber Bragg grating. The coated part of the sensor is fixed, and the displacement is perpendicularly loaded at the end of the fiber sensor.

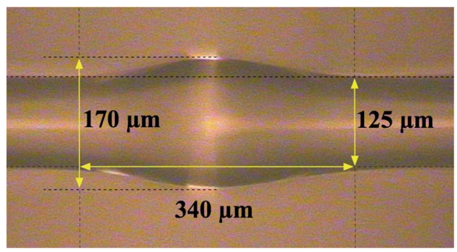

Fig. 2. Microscope photo of the up taper with an enlarged waist diameter of 170 μm.

[13] in the grating region. However, this mode coupling is relatively weak compared to the aforementioned mode coupling mechanisms, due to the limited overlap integral between the pair of cladding modes [14].

The up taper is fabricated by the fusion splicer from Fujikura (FSM-40PM), under the normal SMF to SMF fusion model. The excessive fusion is achieved by tuning the "overlap" parameter in the setting menu (which we define as the "taper depth") much larger than the default of 4 μm. As in this study the taper depth will be our main concern, all other settings like pre-fusion time and fusion current are kept in default. After heated by the pre-fusion arc discharge, the flat cleaved fiber ends are softened and pushed towards each other precisely. The arc-discharge with the excessive fusion results in a waist-enlarged fiber structure with a smooth surface. Fig. 2 shows a microscope image of an up taper whose taper depth is 280 μm. The resulted taper length and taper waist are approximately 340 μm and 170 μm, respectively.

3. Experiment and Discussion

3.1. Mode-Coupling Capability of the Up Taper

The core-cladding coupling efficiency of the up taper greatly depends on the taper depth. Fig. 3(a) shows three reflection spectra of the cladding mode recoupling structure with different taper depths and the same FBG. Firstly a fiber up taper with the taper depth of 160 μm was fabricated upstream from the FBG. Compared to the original reflection spectrum of the FBG, it is shown that the core mode experiences some loss slightly, and weak cladding mode resonant wavelengths can be observed in the short wavelength region. When another up taper with a taper depth of 250 μm was formed by splicing the same FBG with the interrogation fiber, the cladding modes are relatively stronger. On the other hand, the core mode experiences an even larger loss that reaches approximately 15 dB, as it experiences twice the loss of the up taper. Other taper depths were experimented and the appropriate ones were chosen in the following sensing applications.

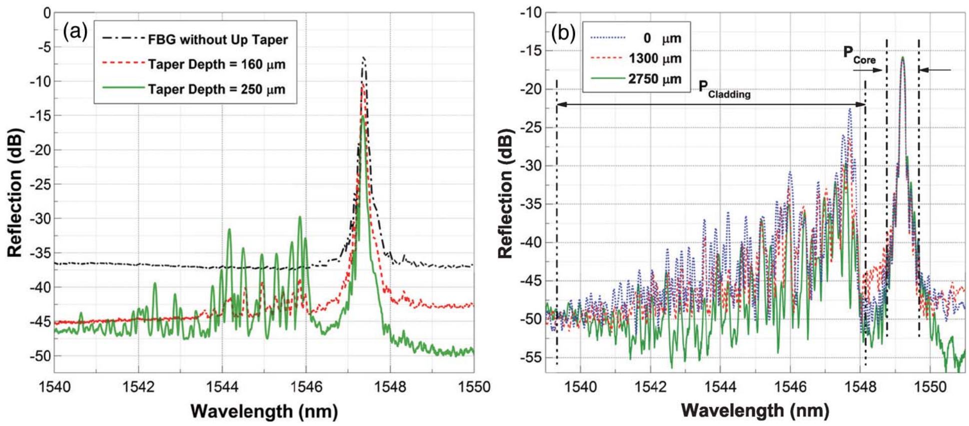

Fig. 3. (a) Cladding-mode backward recoupling effects versus the taper depth. (b) Reflection spectra responses to three displacements by cascading the up taper and a normal FBG.

3.2. Responses of the Cladding Modes and Core Mode to the Displacement

The spectra responses of the cladding modes and the core mode to the variance of the displacement are studied [Fig. 3(b)]. An FBG with the reflectivity of more than 90% and the grating length of 9 mm was used. The taper depth of the up taper was carefully tuned to 250 μm. A distance of 10 mm between the up taper and the FBG was chosen in consideration of the sensor sensitivity and the measurement range. Then the interrogation fiber side of the fabricated sensor was glued between two pieces of glass slides with a free length of 30 mm to keep the sensor fixed, and no protective tube was used. Note that the cladding mode profile is slightly different from the one shown in Fig. 3(a), this could be induced by the difference in the refractive index (RI) profile of the FBGs which has a direct connection to the mode recoupling mechanism [14]. Other contribution to this difference comes from the fabrication process of the up taper, small cleaving angle before the fusion could result in minor difference in the waveguide structure of the up taper. To make the sensitivity consistent on large scale production, this cleaved angle should be minimized. Despite the distinction in the cladding mode profile, this problem can be eliminated in the power interrogation method since only the reflected cladding mode power is concerned. An optical band-pass filter with an insertion loss of 5 dB was placed before the OPM. The filter profile to the cladding modes and the core mode is depicted in Fig. 3(b). Power interrogation was then realized by feeding the filtered reflection power into the OPM.

The displacement was loaded at the free end of the sensor, perpendicularly, via a precise translation stage (Fig. 1). Cladding modes in both energy coupling loops attenuate with the bending for two reasons: mode coupling efficiency at the fiber grating and the up taper reduces [10], and the bending induced propagation loss increases. Since each cladding mode owns its specific intensity distribution, their reaction to the bending is different, as shown in Fig. 3(b). However, the total reflected cladding mode power decays monotonously within a broad displacement range. Fig. 4 depicts the reflection power against the displacement. As the displacement increases, the cladding modes experience a monotonous weakening. Unlike that in [6], the core mode power keeps almost constant, which proves that the core to cladding mode coupling at the up taper region is not affected by the bending. Displacement to both plus and minus direction was applied to the sensor. Small difference of the responses to the direction could be caused by the nonideal symmetry of the up taper and the excited asymmetrical cladding modes. Another reason to this asymmetry is the pre-bending induced by the self-weight of the sensor, which makes the sensing configuration potentially an inclinometer or an accelerometer. The temperature characteristic of the sensor is studied by placing the sensing head under certain bending into a pre-heated oven. Then we let the oven cool down naturally to avoid any possible interference. In the temperature range from 80 °C to 25 °C, the reflected spectrum experiences a shift of about 0.5 nm, while the reflected cladding mode power

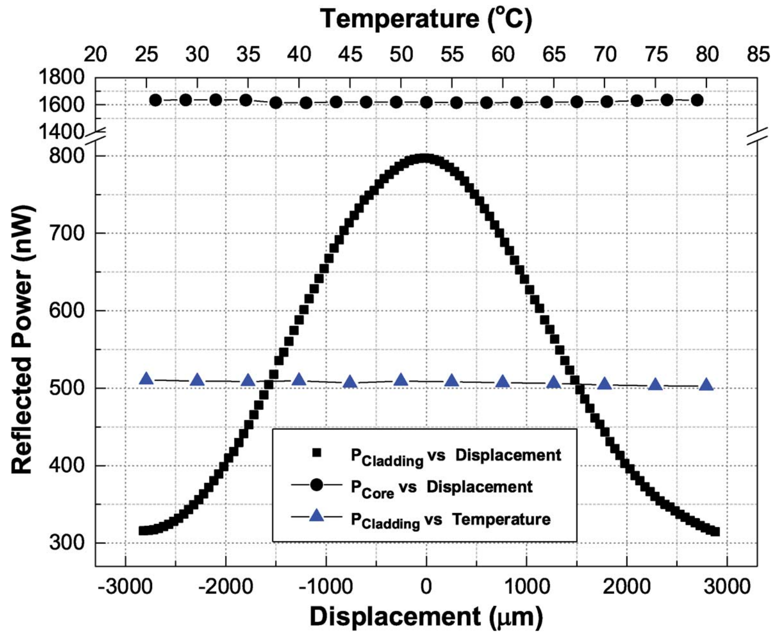

Fig. 4. Cladding mode power and core mode power against the displacement and cladding mode power against the temperature.

perturbation is within 10 nW. Compared to the reflected power that owns a dynamic range of nearly 500 nW, this sensing configuration shows excellent temperature insensitivity.

3.3. Improve the Reflection Power by Using the CFBG

The reflected cladding-mode power is relatively weak (less than 1 μW) due to the high coupling loss at the up taper and the low coupling efficiency at the fiber grating region. Compared to the conventional biconical taper, the loss at the up taper can be relatively high especially when the taper depth turns larger. Low coupling efficiency at the grating region is due to the limited overlap between the cladding mode fields and the fiber core [14]. Low reflection cladding-mode power is a common problem that most sensors based on the cladding-mode backward recoupling encounter [5], [9] even when TFBG that has a higher core-cladding mode coupling efficiency is used. Thus precise OPM is needed in those circumstances. Therefore, we use a uniform CFBG for the cladding-mode backward recoupling. Because of the broader reflection band of the CFBG, the reflection power can be greatly improved [15]. It should be noted that the coupling between counter-propagating cladding modes and core mode in CFBG is usually unwanted, especially in the utilities like dispersion compensation [16]. In our sensor, by incorporating an up taper upstream from the CFBG, the mode coupling capability of the CFBG is fully utilized and the reflected cladding mode power is increased in orders of magnitude.

However, the cladding mode resonant wavelength overlaps with the core modes because of the broad-band characteristic of the CFBG as shown in Fig. 5(a), since the cladding modes always appear in the shorter wavelength region to the core mode. The cladding modes cannot be directly filtered out and separately measured. Hence the dynamic range of the measurement will be greatly reduced as the whole reflection power is measured. Here, in addition to substitute a uniform CFBG for the FBG incorporated in the sensor, the taper depth of the up taper was also tuned to an optimal value of 280 μm under the restriction that the maximum tunable taper depth in the fusion splicer is 300 μm. In this configuration, due to the larger taper depth, the core mode is further suppressed to support better dynamic range of the measurement.

The CFBG used in our sensor has a grating length of 10 mm, and the reflection bandwidth is approximately 13 nm as shown in Fig. 5(a). Displacement measurement was carried out in the

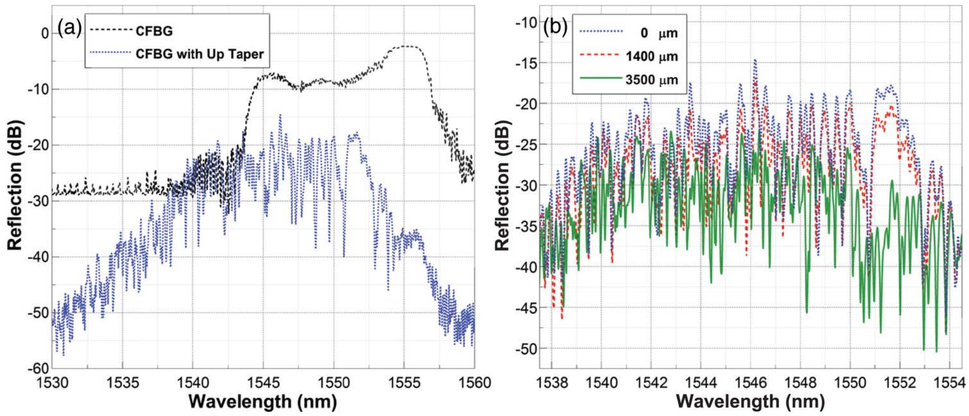

Fig. 5. (a) The reflection spectrum of the CFBG and the configuration by cascading up taper and the CFBG. (b) Part of the reflection spectra responses to three displacements by cascading up taper and the CFBG.

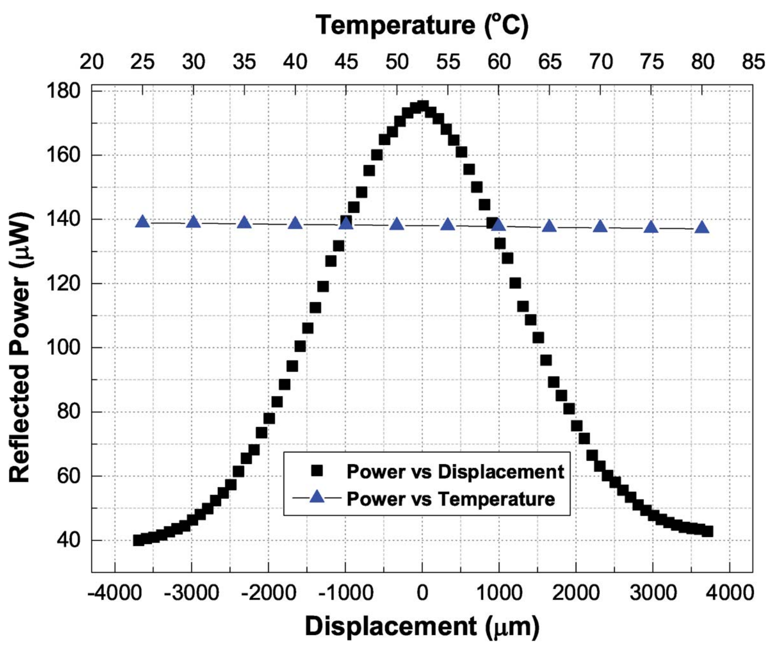

Fig. 6. Reflection power against the displacement and reflection power against the temperature by cascading up taper and CFBG.

same experiment set up except that no optical band-pass filter was used. The reflection spectra evolution against the displacement is shown in Fig. 5(b), where the wavelength range from 1538 nm to 1554 nm is depicted for clearer observation. The reflection power versus the displacement is shown in Fig. 6 in which the power fluctuation induced by the temperature is also depicted. The signal-to-noise ratio to this configuration is slightly worse than that shown in Fig. 4 which has a smoother response curve. The deviation of the reflection power in the measurement is limited to 1.4 μW. This deterioration is mainly due to the broader measuring bandwidth, since the power fluctuation in the BBS has a more severe impact on the measurement result. This fluctuation could be reduced by either using CFBG with narrower reflection bandwidth or employing another OPM to monitor and cancel out the perturbation from the BBS. Experiment to the temperature characteristic was also carried out. Compared to the whole power change of 136 μW, the temperature induced perturbation is limited to 1.8 μW. Thus, temperature cross-sensitivity is also well suppressed in this configuration. In addition, by loading an orthogonal displacement on the sensor, we also tested the direction dependency which is ignorable by virtue of the symmetry of the CFBG and the up taper.

Under the same injection power of the BBS, the maximum reflection power is increased to 176 μW. Without the optical band-pass filter, the reflection power consists of three parts: the core mode power, the recoupled cladding mode power and the broad-band reflection from the end of the sensor stub. It should be stressed that as the taper depth is tuned to 280 μm, the ratio between the cladding mode power and core mode power alters dramatically. Therefore, the energy coupling of loop 2 constitutes the dominant mode coupling mechanism. The core mode power is further suppressed (to less than 40 μW) in this configuration to gain a better dynamic range of measurement. Compared to the mode coupling method that utilizes the special fiber sandwiched structure [15], the up taper in our sensor provides a much controllable and intuitive tuning solution in real usage.

4. Conclusion

In summary, we have experimentally demonstrated the potential of the up taper in the cladding-mode backward recoupling based fiber-optic displacement sensor. The up taper acts as the bridge between the cladding modes and fundamental core mode, which is validated by cascading the up taper with an FBG and observing the reflection spectra. By focusing on the influence of the taper depth on the mode coupling capability of the up taper, two sensing configurations for displacement measurement have been investigated. In the FBG configuration, the recoupled cladding mode power decays as the displacement increases while the core mode power keeps almost constant. Aiming to solve the problem of low reflection power, a uniform CFBG for cladding mode backward recoupling is used, and the reflection power can be increased by orders of magnitude. The reflection power ranges from 40 μW to 176 μW within the maximum displacement range of 3750 μm. In addition, by choosing appropriate taper depth of the up taper, the power ratio between the reflected cladding mode power and core mode power can be tuned to achieve better dynamic range of the measurement in the CFBG configuration. The excessive splice based up taper ensures the strength of the sensor and lowers the difficulty in the process of the package. Moreover, in the CFBG configuration based displacement sensing system, only a coarse OPM is needed to interrogate the displacement information, which makes the sensing system much simplified and potentially low cost.

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