Improvement on Optical Microfiber Fabrication Control Technique by Monitoring Mode Cutoff Position

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Abstract— By monitoring the intermodal interference pattern, we realize online diameter calibration during optical microfiber (OM) tapering process. By a comparison of LP_{02} mode cut-off position between theoretically prediction and the actual monitoring result, we introduce modifications of tapered parameters, and realize an online and precise feedback control in the OM tapered process. Our online feedback control technology provides an effective tool in acquiring high quality OMs by improving the tapered accuracy while maintaining good repeatability, which is essential for applications in scientific research and engineering areas.

1. INTRODUCTION

Optical microfiber (OM) has been concerned for its special characteristics such as large evanescent field, high disperse and strong nonlinearity et al. [1]. Many works had been performed to try to get OM with various fabricating technologies. An OM with conventional optical fiber as pigtails has been paid more attentions for its convenient application. Although the manufacture and application of OM have obtained much development, some problems still exist in aspects such as production process, transmission loss, and uniformity of waveguide structure et al., which may not meet the requirement of engineering and scientific research [2]. For example, in research areas such as atomic trapping [3, 4], sensing technique based on evanescence field [5, 6], the production monitoring technology should be exploited to ensure the characteristics of OMs reliable in practical applications.

The OM fabrication monitoring systems had been studied by many people to ensure well optical transmission properties. The monitoring systems constructed with different devices were used. A combination of white light source and optical spectrum analyzer can be used to get the evolution of the transmitting spectrum of the tapering fiber during the whole tapering process. Another combination of laser source and photo-detector can be used to get the evolution of excited modes based on the intermodal energy transfer [7–10]. In this paper, we want to enhance the interference phenomenon in the tapering fiber during the fabrication process of OM, by choose a high coherent laser as the monitoring light source, and use a power jumping point in the monitoring signal corresponding to the normalized cut-off frequency of the LP_{02} mode to judge the diameter of the fabricated OM. So, by using different online feedback methods to adjust the tapered parameters, the OM tapered accuracy could be improved.

2. ANALYSIS OF INTERMODAL INTERFERENCE CHARACTERISTICS IN OM MANUFACTURE PROCESS

In this paper, the OM tapering device was set up based on a widely used modified flame-brushing technique [11], shown in Figure 1. A telecom fiber (SMF-28, Corning) is clamped onto the two motorized precision translation stages and stretched under the control of computer, while the bare part of the fiber is heated by a micro-heater (CMH-7019, NTT-AT). Both stages and micro-heater are automatically controlled by a computer. One end of the drawn fiber is connected with a high coherent laser source (RIO, 1550 nm, line width 2 kHz). The other end is directly connected to the detector (OE-200). Based on the model in Ref. [12], OMs with different structure and transmission characteristics can be tapered, by precisely control of parameters such as heating zone length, heating temperature, tapered velocity, cone angle et al..

In different stages of tapered process, as the decrease of waist diameter, the fundamental mode in the original core will expand into the clad, shown in Figure 2. The mode will transmit in the new "core", which consists of the original clad layer and the new air clad, that form a "clad-air clad mode". By the normalization equation:

$$V = \frac{2\pi a}{\lambda_0}\sqrt{n_{core}^2 - n_{clad}^2} \tag{1}$$

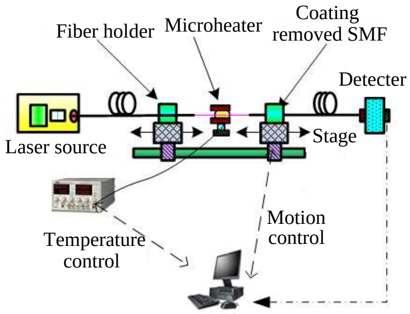

Figure 1: Schematic illustration of the OM fabrication setup.

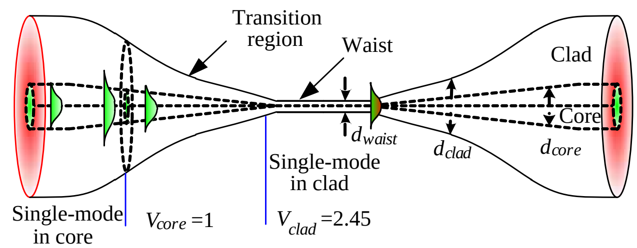

Figure 2: Schematics of typical structure and mode transmission in OMs satisfying adiabatic condition.

We could know that, in the tapered process, the permitted mode numbers in waist region will first increase and then decrease [9, 10]. When the waist diameter decreases to a single mode limited value, only the fundamental mode transmits in the waist.

In tapered process, waist parameters will be affected by factors such as the change of heating temperature, tensile strain et al.. When the waist region permits multimode transmission, higher mode will be excited. Due to different transmission constant, phase differences exist among modes when transmit a distance, and induce intermodal interference. The fundamental mode is rotational symmetrically, when the waveguide symmetry is kept well in tapered process, only LP_{0m} mode could be excited. Ignoring the radiation mode and bending influence, the intermodal interference intensity distribution is described as [13]:

$$I(r,z) = E(r,z)E^*(r,z) = \sum_{m=1}^{M}\sum_{n=1}^{M} c_m c_n^* E(r,z)E^*(r,z)\exp[i(\beta_m - \beta_n)z] \tag{2}$$

where c_m is the coupled coefficient between fundamental mode and LP_{0m} mode, β_m is the transmittance constant of higher mode, z is the transmission distance. Under influence of changed heating temperature and tensile strain, c_m, β_m and z will be modulated, and the interference pattern changes correspondingly that could be detected.

When the waist diameter become smaller to a certain value, higher modes will be cut off, and will result in a change of the intermodal interference pattern. We can see that, when LP_{02} (HE_{12}) mode is cut off, at most LP_{01} (HE_{11}) and LP_{11} (TE_{01}, TM_{01}, HE_{21}) are permitted (in cases of disturbing such as bending). When LP_{02}(HE_{12}) is cut off, the corresponding OM diameter is about 1.8 µm. Now the diameter scale of OMs is mainly in the sun-wavelength range. For example, the most common applied OMs have a diameter range of 0.5∼2 µm [1, 2]. Our experiment also shows that, the tapered device has a relatively larger error when the waist diameter becomes smaller than 4 µm, and we can utilize this featured position (when LP_{02} mode is cut off) to scale the diameter of the tapered fiber, and improve the tapered accuracy.

In order to monitor the intermodal interference during the fabrication process of OM, A high coherent laser (RIO Company) with no less than 2 kHz line width is chosen as the light source. Corresponding parameters were set up in order to fabricate an OM with waist region diameter about 1 µm and waist length about 10 mm. The output light of the tapering fiber was detected with a detector sampled by an A/D converter with 100 Hz sampling frequency.

3. FABRICATION CONTROL TECHNIQUE BASED ON MONITORING INTERMODAL INTERFERENCE

The theoretical analysis results show that, by using high coherent light source to online monitor the OM tapered process, the jump point could be detected when the mode cut off, and the phenomenon be especially obvious when the LP_{02} mode cut off. For this reason, we use this intermodal interference featured point to establish the diameter in the OM tapered process, and add feedback control to adjust the tapered parameters, which may increase the tapered accuracy and stability.

In the tapered process, by set tapered parameters: taper uniform waist length $l_w = 10$ mm; taper waist diameter $d_w = 1$ µm; taper speed $v = 100$ µm/s; liner revise factor $a = 0.1$ [12]. Then we use many methods including compensated control of initial heating width, suppress the circumstance noise, and adjust the temperature, to make the intermodal interference jump point maximally close to the theoretical LP_{02} mode cut off position, and then detect the acquired OM in the microscope. Figure 3(a) shows the online monitoring of OM sample. It can be seen that the difference between LP_{02} mode's theoretical cut off position and intermodal interference jump point is 1.829 s, by which we could infer that the diameter error between prediction and actual result will in 0.01 µm. The measured the diameter of the sample by microscope is 1.03 µm, see Figure 4. Figure 3(b) is the theoretical diameter in the tapered process. The red line and the three asterisk points respectively represent the theoretical result and the measured values, which are in good agreement. From the monitoring result, we can see that the transmission loss is as low as 1%. The additional loss after tapered process mainly comes from the circumstance pollution, and the pollution sensing could be realized by measuring this additional loss [5, 6].

The above experiment sufficient demonstrated the effectiveness of the diameter establish method by using intermodal interference jump point (LP_{02} cut off), and the OM tapered error is expected to be deceased below 2%.

Additionally, we have made 3D transmission spectrogram of the sample's monitoring result, see Figure 5. We can see that, two main routing evolutions of interference appeared in the tapered process, which means that two higher order modes were excited [7–10, 14]. At about 450 s, the first routing evolution disappeared which represents the cut off of one of the high order mode, and at about 510 s, the second routing evolution disappeared with clear dividing line, which is the LP_{02} cut off point.

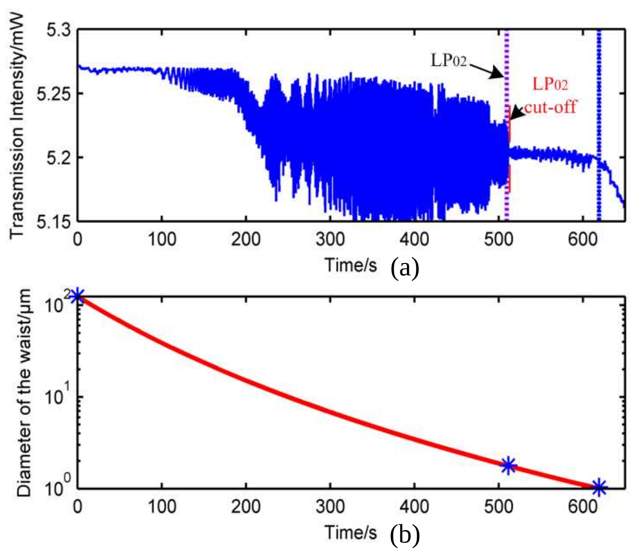

Figure 3: (a) Online detection of OM sample and (b) diameter measurement and theoretical prediction in the tapered process ($l_w = 10$ mm, $d_w = 1$ µm).

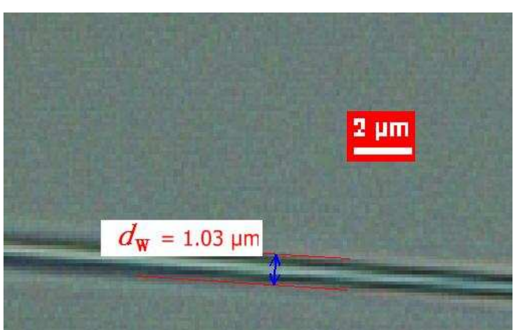

Figure 4: Images of the OM sample-2 in optical microscope ($l_w = 10$ mm, $d_w = 1$ µm).

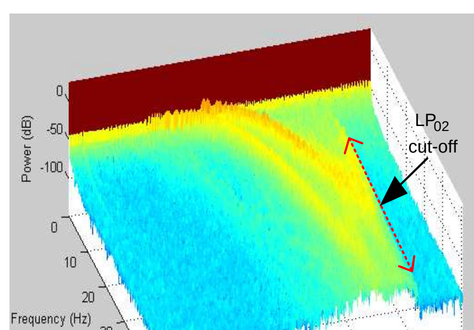

Figure 5: The 3D transmission spectrogram of the sample-2's monitoring result ($l_w = 10$ mm, $d_w = 1$ µm).

In practice, different OMs with different parameters will be required. The diameter of OM is usually estimated according to volume conservation rule. But the estimated diameter value may not be correct due to the different tapering conditions such as environment temperature or the variation of the fabrication devices. Now, we can judge the diameter accuracy just by measuring the time of the jumping points during the fabrication process with the optical monitoring system. According to the last jumping point in the time domain signal, we can deduce the terminal diameter of the OM and modify the parameters so as to ensure a correct diameter monitor for the OM fabrication monitoring system.

Three methods have been used to decrease the errors that mentioned. First, use compensation tapering based on the delay between actual and predicted jump point. Second, due to the fact that the error keeps stable at the same tapered parameters and conditions, we can make one sample to establish the error, and then add proper modifications. For the OM itself, the influence of the length of tapered waist (l_w) on optical characteristics could be ignored, but the diameter influence is obvious (d_w). So we can change the l_w while keeping other parameters unchanged, especially for d_w to decrease the tapered error. So we can decrease the diameter error by just change the single variable l_w. Third, from the mentioned error analysis, we can see that the initial heating width of the tapered volume is an inevitable and important factor to induce tapered error. And we can attribute all the error factors to the heating width error. So we can compensate the initial heating width to realize modification while keeping OM's waveguide structure unchanged. For the three methods mentioned here, repeated experiments demonstrated that the tapered structure error could be controlled below 5%.

Through theoretical analysis and experiment, the last jumping point is corresponding to the time when the LP_{02} mode is cut off in the tapering fiber process. We can calculate the normalized frequency of the tapering OM and deduce the diameter of the tapering OM at that time, and also can obtain the diameter of the OM combining the initial diameter of the taper fiber (usually 125 μm) and the theoretical formula of the estimated diameter of the OM. The jumping point characteristic used for judging the diameter of the tapering OM and even to correct the theoretical diameter of the fabricated OM based on the initial fiber diameter, tapering length, OM terminal diameter and others parameters which could be estimated by person or software online. When the deviation between actual LP_{02} mode jump point and theoretical value is large, we can add software online controlled feedback to adjust the tapered parameters. This technology is benefit for large amount production of qualified OMs.

4. CONCLUSION

In this paper, an OM tapering device based on the modified flame-brushing technique was made systematic error analysis and online measurement. The OM fabrication monitoring system is set up with a high coherent laser so as to enhance the interfere effect in the tapering process. The corresponding spectrograph of the OM tapering process is plotted, which is helpful to analyze the evolution of excited modes. A jumping point is used to judge the correction of the calculated diameter of the OM. The results used for obtaining OMs with accurate structural parameter. So, by using different online feedback methods to adjust the tapered parameters, the OM tapered accuracy could be improved. The intermodal inference based online monitoring method in OM tapered process will improve the technological level of OM production, and make the OMs more qualified in scientific and engineering applications.

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