Tunable Optical Bandpass Filter via a Microtip-Touched Tapered Optical Fiber

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We demonstrate a tunable bandpass optical filter based on a tapered optical fiber (TOF) touched by a hemispherical microfiber tip (MFT). Other than the interference and selective material absorption effects, the filter relies on the controllable and wavelength-dependent mode–mode interactions in TOF. Experimentally, a large range of tunability is realized by controlling the position of the MFT in contact with the TOF for various TOF radii, and two distinct bandpass filter mechanisms are demonstrated. The center wavelength of the bandpass filter can be tuned from 890 nm to 1000 nm, while the FWHM bandwidth can be tuned from 110 nm to 240 nm when the MFT touches the radius range from 160 nm to 390 nm. The distinction ratio can reach $28 \pm 3$ dB experimentally. The combined TOF-MFT is an in-line tunable bandpass optical filter that has great application potential in optical networks and spectroscopy, and the principle could also be generalized to other integrated photonic devices.

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Tunable optical filter is necessary in many practical applications for increasing signal-to-noise ratio by rejecting unwanted backgrounds. Traditional optical filter is mainly made by dispersive absorptive materials or interferometer. The first approach is insensitive to the configuration of the setup, and therefore the filter bandwidth and center wavelength are hardly tunable. The other approach is sensitive to the change of optical paths. Consequently, a change of geometry by external controller and refractive index (RI) due to varying temperature or the angle of incident light would modify the optical response of the device. Recently, there has been increasing interest in processing optical signal by optical fiber, and optical fiber filters are key components and play a significant role in applications from optical communications and spectroscopy to wavelength division multiplexing networks. Therefore, the broad tunability of optical fiber filters is in demand.

Similar to their bulk counterparts, the optical fiber filters are demonstrated through interference. The tunability of filters, such as Fabry–Pérot interferometer, has been demonstrated by tuning cavity length, thermal tuning, strain, an angularly tunable commercial optical fiber, resonant optical tunneling, and liquid crystals. In contrast to free-space optical components, the optical fiber offers new possibility by exploring the micro-/nano-photonics structures. For example, by stretching a standard single-mode fiber while heating it, a tapered optical fiber (TOF) can be fabricated by standard fibers. A TOF with an ultrathin waist at the sub-wavelength level can offer strong transverse confinement of the guided modes, resulting in the spread of a considerable evanescent field surrounding the TOF. By exploiting the evanescent field, fiber loop, or knot resonators, and TOF couplers have been realized and in-line filtration of optical signal has also been realized. Alternatively, long-pass or short-pass filter has been reported in the TOF, based on the guided mode in the TOF to unguided mode coupling. The long-pass is due to the non-adiabatic mode conversion of the taper region, where high-order modes are excited and consequently rejected by the single-mode nanofiber segment. The short-pass is realized by immersing the micro-/nano-fiber in high RI environment, and the guiding mode would be leaked to the environment when the effective RI of the propagating mode is lower than the RI of environment.

In this work, we propose and demonstrate a novel method of constructing a TOF-based bandpass optical filter that can be tuned widely. Theoretically, we sum-

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marized the essential principles of mode–mode interactions for the light filtration in TOF, and proposed two mechanisms of tunable bandpass in-line filter. Distinct from the interferometer and material absorption approach, the filter is tunable by reconfiguring the micro-photonic structure, while is robust against experimental imperfections. Experimentally, we use a hemispherical microfiber tip (MFT) of tens of micrometers in diameter to control the mode–mode interactions and verify the tunable bandpass filter. The center wavelength and FWHM bandwidth can be widely tuned when the MFT touches the TOF at different radii. The proposed tunable optical fiber bandpass filter based on a TOF-MFT system provides a new kind of in-line optical devices, and has great application potential in optical networks and spectroscopy.

To provide a comprehensive explanation about the principle, we plot the effective RI of a TOF \( (n_{eff}) \) as a function of the wavelength, as shown in Fig. 1(b). At any cross-section of the TOF, the modes are the solutions to the characteristic function of a uniform and isotropic cylinder with RI of \( n_s = 1.45 \) surrounded by the air cladding RI of \( n_{air} = 1.0 \), which is only determined by the dimensionless number \( k_r \), where \( k = 2\pi/\lambda \) is the wavelength, and \( r \) is the radius of the cross-section. Figure 1(b) can be interpreted in two distinct ways: i) as shown by the bottom horizontal axis, the effective RI of mode \( (n_{eff}) \) is a function of wavelength \( (\lambda) \) for a fixed TOF radius \( r = 250 \) nm; ii) as shown by the top horizontal axis, \( n_{eff} \) is a function of \( r \) for a fixed input wavelength \( \lambda = 1000 \) nm. In Fig. 1(b), the red solid line and the blue dotted lines stand for the fundamental HE_{11} mode and the first higher-order mode group (TE_{01}, HE_{21}, and TM_{01}), respectively. In Fig. 1(b), we can find that only fundamental mode survives in the fiber with radius \( \lambda > 686 \) nm or \( r < 365 \) nm. This is because of the single-mode cut-off condition \( 2\pi \sqrt{n_s^2 - 1}/\lambda = 2.405 \), i.e., \( r/\lambda \approx 0.365 \).

We explain the three mode–mode interaction (MMI) effects as follows:

(i) MMI-1. The conversion between guided modes in taper region [Fig. 1(c)]. For varying TOF radius, the guided modes \( a_k(z) \) evolves with the TOF axis \( z \) as

\[
\frac{\partial}{\partial z} a_k(z) = - \left( \frac{\psi_l(z)}{\psi_l(z)} \right) \frac{\partial}{\partial z} \psi_l(z) a_l(z) - \sum_{m \neq l} g_{lm}(z) e^{i [\beta_m(z) - \beta_l(z)] dz} a_m(z).
\]

Here, \( \psi_l(z) \) is the eigenmode at \( z \) with the wavevector \( \beta_l = n_l k \), \( n_l \) is the effective RI of the \( l \)-th mode, and the mode–mode coupling strength is

\[
g_{lm}(z) = \left\langle \psi_l(z) \left| \frac{\partial}{\partial z} \right| \psi_m(z) \right\rangle.
\]

Ideally, for a very slowly varying radius, i.e., a very small taper angle, \( g_{lm}(z) \) is negligible compared with the effective propagation constant difference between modes \( \Delta \beta = \beta_m(z) - \beta_l(z) \). Thus, the input fundamental fiber mode could adiabatically evolve to the fundamental mode in the nanofiber. However, the MMI-1 occurs in the taper region. Because the core diameter decreases along the TOF in the taper region, effective propagation constant difference between fundamental and higher-order modes \( (\Delta \beta) \) is smaller for shorter wavelength, which means that these modes are very crowded for shorter wavelengths.

![Fig. 1.](image)
These modes can extend into the cladding. The modes are guided as higher-order modes by the cladding–air interface, because the cladding radius is much larger than the single-mode cut-off radius. When reducing the fiber radius to a few hundreds of nanometers, as shown by the top axes in Fig. 1(b), the higher-order modes are cut-off due to the adiabatic condition. The MMI-1 depends linearly on the taper angle and increases with smaller wavelength.\footnote{31} Therefore, the modes with small wavelength are blocked. In addition, such a long-pass effect has also been experimentally reported and discussed in Ref.\footnote{32}.

(ii) MMI-2. The coupling between the guided mode and the continuum of unguided modes in MFT \cite{33} [Fig. 1(d)]. In the uniform nanofiber region, the extra MFT induced short-pass function. The mechanism is similar to that underlying the results reported in,\footnote{34} where short-pass filter is achieved by introducing a MgF substrate to a TOF. When MFT approaches the nanofiber region, there is evanescent coupling between the guided fundamental mode with the unguided modes in the MFT. With respect to the guide mode in nanofiber, the MFT has a much larger geometry size and could be treated as an infinite large substrate. According to the coupled-mode theory derivation about the interaction between guided optical mode and the continuum of unguided modes in substrate, we have the propagation loss of guided mode with two-dimensional approximation as\footnote{34}

\[ L \propto \frac{1}{(n_0^2 - n_{\text{eff}}^2)^{3/2}} e^{2kd\sqrt{n_{\text{eff}}^2 - 1}}. \]  

Here, \( d \) denotes the distance between the nanofiber and the MFT. We should note that the estimation is only valid to the perturbation approximation, i.e., the portion of the guided mode energy that penetrated to the MFT is much smaller than unity. According to Fig. 1(b), larger wavelength has smaller \( L \), and thus the MMI-2 gives a strong wavelength-dependent loss \( e^{-L/2} \) with the MFT-TOF tough region length of \( L \), and eventually gives rise to the short-pass function.

(iii) MMI-3. The coupling between the guided mode and the continuum of unguided modes in air \cite{33}. For \( n_{\text{eff}} \) close to 1 with \( r/\lambda \ll 1 \), the guide mode in the nanofiber region is weakly confined and a large portion of energy is distributed outside the dielectric, with a field decay length of \( 1/k\sqrt{n_{\text{eff}}^2 - 1} \gg \lambda \). In this case, the perturbation approximation of MMI-2 is not valid anymore. In this case, the guided mode could also couple with the free space continuum modes, which have effective RI \( < 1 \). Here, we could treat the mode–mode couplings as the free-space scattering as if propagating beam is scattered by the MFT, and thus induces the coupling between guide modes and the continuum of unguided modes in air. More intuitively, we could treat this as a diffraction process, and part of the input laser beam could bypass the MFT and is collected by the TOF. Therefore, for longer wavelength beyond the MMI-2 regime, the light could be partly transported through the MFT-touched TOF. For even longer wavelength (\( n_{\text{eff}} \approx 1 \)), the guided mode in TOF almost spreads to free space and is extremely sensitive to the bending of the nanofiber. Thus, the long wavelength is eventually rejected by the device.

Therefore, we can simultaneously have two different mechanisms of realizing bandpass filter: i) the combination of the long-pass of MMI-1 at the taper region and short-pass of MMI-2 at the MFT-touched region; ii) the MMI-3 for weakly confined modes in nanofiber for \( \lambda \gg r \). In this work, MMI-1 is fixed for a prepared TOF, while the location of the MFT is controllable. Comparing the analysis in the above interactions, we can find that the \( kd \) and \( kr \) are the dimensionless numbers that determine the optical losses in MMI-2 and MMI-3. Thus, the wavelength range of the bandpass filter can be controlled by the location of MFT (\( d \) or \( z \)). For the robustness of the device, we choose \( d = 0 \), only change the \( z \) to adjust \( r(z) \), and essentially realize the tunable bandpass filter.

In Fig. 2, we numerically verified the MMI-2 and MMI-3 in MFT-touched nanofiber \cite{33,34} for various \( r \). Wavelength-dependent RI is used for the TOF and the MFT. We simulate the transmission spectra by three-dimensional finite difference time-domain (3D FDTD) method (Lumerical Solutions, Inc.), with the light with a uniform spectrum launched into the fundamental mode of the nanofiber. Since the polarization of the light source is natural and we just show the average of the two orthogonal polarizations. As shown in Fig. 2(a), the long wavelength (\( \lambda > 800 \text{nm} \)) is blocked by the MFT, confirms the prediction of MMI-2. As an example, we plot the field distribution in the nanofiber and MFT, the guided modes are all leaked to the MFT and are guided along the MFT to other output ports. It is worth noting that the leakage looks like a beam that is refracted from the tip, with its refractive angle determined by the effective RI of the guide mode, as predicted by the system–environment interaction theory.\footnote{34} In addition, since the perturbation is small and \( n_{\text{eff}} \gg 1 \), the scattering by the MFT to free space is negligible. In Fig. 2(a), when reducing the radius from 390 nm to 160 nm, the corresponding cut-off wavelength shifts to shorter wavelength, as the scaling of \( \lambda/r \) should be invariant. We also note that for the results about the radius at 161 nm and 194 nm, although the cut-off wavelength is smaller than 600 nm, there is an additional bandpass window around 1000 nm, which verified the MMI-3. The inset of Fig. 2(a) illustrates zoom-in of the curves with a nanofiber radius of 161 nm and 194 nm. Figures 2(c) and 2(d) plot the Poynting vector distribu-
tion for $\lambda = 970$ nm and 1500 nm. We could discern the transmitted light through the nanofiber. Comparing the two figure to $\lambda = 750$ nm in Fig. 2(b), we find that the input guided modes are weakly confined in the nanofiber, and the diffraction pattern in the air is obvious. For longer wavelength 1550 nm, the collection of energy in the nanofiber is less efficient. In Figs. 2(b)–2(d), to show the scattering clearly, the Poynting vector is normalized to the maximum.

![Fig. 2.](image)

Fig. 2. (a) Numerical simulation of the transmission spectra of the TOF touched by the MFT for different TOF radii from 160 nm to 390 nm. Inset: zoom-in of the curves with nanofiber radius of 161 nm and 194 nm. (b)–(d) Poynting vector distribution in the $x$–$z$ plane when the input wavelengths are 750 nm (b), 970 nm (c), and 1500 nm (d), respectively. Here, the nanofiber radius $r = 161$ nm.

![Fig. 3.](image)

Fig. 3. (a) Schematic diagram of the experimental setup for measuring the transmission spectra of the bandpass filter. (b) Typical SEM image of the TOF. The inset shows a full radius profile of the TOF measured via SEM. (c) Photograph of the MFT.

The experimental setup for measuring the transmission spectra of the bandpass filter is shown schematically in Fig. 3(a). A quartz tungsten halogen light source (SLS201 L/M, Thorlabs) is collimated and coupled into a single-mode optical fiber by a fiber coupler. The power is more than 10 mW. The wavelength range of the light source is 360–2600 nm. The light passes through a TOF, and the spectra of the filter are measured by an optical spectrum analyser (OSA, 86142B, Agilent).

The TOF was fabricated from a single-mode fiber (SM800, Fibercore) using the flame-brush method. Our flame-brush setup consists of three computer-controlled high-precision motors. A regular single-mode fiber is pulled by two motors, while the third motor is used to move the torch to form a traveling hydrogen/oxygen flame. Therefore, the regular single-mode fiber is melted and narrowed. For the device studied in this work, the radial TOF profile was measured via scanning electron microscopy (SEM) as a function of the position along the TOF axis. Figure 3(b) shows a typical SEM image of the uniform nanofiber region. The minimum radius of the uniform part can reach 150 nm, and the inset shows the full radius profile of the TOF. The total TOF consists of three parts: i) a normal single-mode fiber with a ra-
The diameter of the MFT is 52 µm. The MFT fabrication setup and procedures are discussed in Ref.[35]. A photograph of the MFT is shown in Fig. 3(c). The diameter of the MFT is 52 µm, and the MFT was utilized in the experiments described below. A three-axis piezo stage with nanometer resolution (P-611.3, Physik Instrumente) was used to move the MFT to bring it in contact with the TOF with high spatial resolution. The free length of the MFT beyond its anchored position is less than 1 mm. The setup is housed inside a two-layer glass cover to avoid the influence of air currents and dust. Two perpendicular optical microscopes are used as an auxiliary equipment to monitor the positions of the TOF and the MFT. When the MFT is close to the TOF, the TOF transmission decreases with decreasing TOF-MFT distance. Once the MFT touches the TOF, the TOF transmission reaches a stable value and does not change anymore when the MFT keeps moving, because the TOF is stuck with the MFT by the van der Waals force. This configuration is robust enough for the vibrations from environment. Therefore, we can determine whether the MFT touches the TOF or not by the TOF transmission eventually.

![Fig. 4. Transmission spectra of the source, TOF, and MFT-touched TOF for a broadband source.](image)

The advantage of the MFT is that the tip is insensitive to the configuration and angle of the TOF and MFT. Therefore, it is very convenient to change the position of the MFT to interact with the mode at different radii. In our experiments, to tune the bandpass filter, we brought the hemispherical MFT in contact with the tapered part and moved it along the axis of the TOF. Figure 5(a) shows the normalized transmission spectra of the bandpass filter when the TOF is touched by the MFT at various TOF radii from 160 nm to 390 nm. We can find that the overall transmission reduces when the nanofiber radius is reduced from 390 nm to 280 nm, due to the shifting of long cut-off wavelength (due to MMI-2) towards the short cut-off wavelength (due to MMI-1). When \( r = 280 \text{ nm} \), we could find that the light with almost all wavelength is blocked by the MFT-touched TOF. However, when we further reduce the radius, a bandpass window appears again around 1000 nm, and shifts to shorter wavelength when the radius is even smaller. The properties of tuned bandpass filter are summarized in Fig. 5(b). We can find that both curves of center wavelength and bandwidth jump around \( r = 300 \text{ nm} \), so we divide the figure into two regions, corresponding to the two mechanisms of bandpass. When \( r > 300 \text{ nm} \), the mechanism is due to the combined short-pass and long-pass effects by MMI-1 and MMI-2. In this region, it is obvious that center wavelength reduces with reducing \( r \) as expected. When \( r < 300 \text{ nm} \), the center wavelength is around 980 nm and can be tuned to smaller wavelength by reducing \( r \), also confirms the dimensionless \( \lambda/2r \) relation. Comparing the experimental results to the simulation results, we find that the trend of center wavelength and bandwidth with various TOF radius are consistent with each other. Therefore, the experimental results in this region verified that the mechanism of bandpass arise from the effect of MMI-3. For the first
mechanism, the distinction ratio can reach $28 \pm 3$ dB, and the second mechanism gives a distinction ratio reaching $26 \pm 4$ dB. The distinction ratio based on the relation is calculated to be $10 \log \left( \frac{T_{max}/T_{ave}}{T_{ave}/T_{min}} \right)$, where $T_{max}$ is the maximum transmittance and $T_{ave}$ is the average value of the transmittance when the light is blocked by the filter.

In conclusion, we have demonstrated two mechanisms of bandpass filter in an MFT-touched TOF, which promise broadband and robust tunability by the controllable coupling between guided mode and unguided modes through an MFT. When the radius of TOF at the MFT-touched region increases along the axis of the TOF, we observed the transition between two mechanisms (combination of MMI-1 and MMI-2, MMI-3) for the bandpass wavelength around 900 nm. For the MFT-induced guided mode to unguided MFT modes coupling (MMI-2 mechanism), we find that the center wavelength is tuned from 880 nm to 910 nm. For the MFT-induced guided mode to unguided air mode coupling (MMI-3 mechanism), the center wavelength can be tuned from approximately 960 nm to 990 nm, while the FWHM bandwidth can be tuned from 150 nm to 110 nm. In this work, the best distinction ratio that can be achieved is $28 \pm 3$ dB. There are two limitations for this approach. The first one is the insertion loss. Fortunately, we have some methods to reduce the insertion loss substantially. We can actually optimize the shape of the tapered TOF to reduce the loss. On one hand, the TOF was stretched in three steps with three constant heating lengths. Therefore, the TOF has three taper angles. We can change the number and values of the taper angles or use the gradually variable taper angles to reduce the losses. On the other hand, we can use an MFT with a layer which has low refractive index or change the material and the shape of the MFT to optimize the filter. Another limitation is to choose a proper working wavelength range. In this Letter, the wavelength range is from 600–1200 nm and we can change the sizes of the TOF to make sure that the bandpass filter can work for the wavelength longer than 1200 nm or shorter than 600 nm. As an in-line device, the tunable bandpass filter is small and exquisite after improvement, and is robust and easy to combine with other fibre systems. For practical applications, the filter can be improved in the following ways: i) we can optimize the profile of the TOF to shorten the TOF according to the adiabaticity criterion[13] and MMI-1; ii) the length of MFT can be shortened without degrading the performance of the filter; iii) the high precision stages are not necessary and a small and simple movable structure can be used to tune the MFT as the length of TOF is in centimeter scale and the radius alteration of TOF along the axis is gentle. This method provides a convenient way to tailor the optical losses and the mechanism can also be extended to other waveguide-based photonic devices.

References