Optical Fiber Technology 30 (2016) 89–94

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Design and optimization of fundamental mode filters based on long-period fiber gratings

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ARTICLE INFO

Article history:
Received 6 December 2015
Revised 24 March 2016
Accepted 26 March 2016

Keywords:
Optical fiber devices
Optical fiber filters
Gratings

ABSTRACT

A segment of long-period fiber grating (LPFG) that can selectively filter the fundamental mode in the few-mode optical fiber is proposed. By applying an appropriate chosen surrounding material and an apodized configuration of LPFG, high fundamental mode loss and low high-order core mode loss can be achieved simultaneously. In addition, we propose a method of cascading LPFGs with different periods to expand the bandwidth of the mode filter. Numerical simulation shows that the operating bandwidth of the cascade structure can be as large as 23 nm even if the refractive index of the surrounding liquid varies with the environment temperature.

1. Introduction

The first kind of optical fibers used for optical communication is multi-mode optical fibers (MMFs), however, due to the limits of modal dispersion, MMFs are mainly used in short distance communication. Sing-mode fibers (SMFs) can avoid the modal dispersion, leading to the great expansion of the transmission capacities of optical fiber communication systems. The capacities of SMFs have been exploited by the wavelength-division multiplexing (WDM), polarization-division multiplexing (PDM), and time-division multiplexing (TDM) technologies. However, owing to the nonlinear effects caused by the increased transmission power and the limited mode area of SMFs, the transmission capacity is close to the limit [1]. One of the solutions is to use space-division multiplexing (SDM) technology [2,3], which is based on multi-core optical fibers (MCFs) or multi-mode optical fibers (MMFs). Mode multiplexing in MMFs is difficult to realize owing to the large number of modes in MMFs. Therefore, few-mode optical fibers (FMFs) become a preferred choice. FMFs have aroused a lot of interests recently. FMFs can be used for long-distance transmission without modal dispersion and insertion loss penalty [4,5]. Single-mode operation can be realized by selectively exciting the fundamental mode, leading to large mode area operation [4,5], or low-bending loss operation [6]. It is well known that two-mode optical fibers (TMFs) can be worked as interferometric sensors [7]. Higher-order mode operating with ultra-large effective-area has been demonstrated and proposed as a new strategy for high-power lasers [8]. FMFs can also be designed to possess high-order modes with a variety of desired dispersive properties [9].

Mode tailoring devices, such as mode multiplexers/demultiplexers [10–20], mode converters [21–26], are the basic devices for FMF based applications. For example, mode converters should be used to convert between the fundamental mode in SMFs and the high-order modes in FMFs. One kind of the most commonly used mode converters is the long-period fiber grating (LPFG) based mode converter [18,21,27], which can ensure high conversion efficiency between the fundamental mode and the converted high-order mode. However, owing to the fact that the two core modes are propagating in the same core, the rest of the fundamental mode will become a source of cross-talk to the converted high-order mode. Generally, for communication applications, a high conversion efficiency of 20 dB is needed in order to suppress the fundamental mode. The operating bandwidth of the mode converter can be expanded effectively if more moderate cross-talk criterion can be accepted. Meanwhile, a mode filter that can selectively filter the fundamental mode and preserve the high-order modes simultaneously, can be applied to suppress the induced cross-talk. Mode filters can be used to suppress the unwanted modes during the demultiplexing process. Just like wavelength filtering devices for WDW systems, mode filtering devices should also be a basic component for mode-division multiplexing (MDM) systems.

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http://dx.doi.org/10.1016/j.yofte.2016.03.006
1068-5200/

In this article, an LPFG configuration that can operate as a mode filter is numerical demonstrated. In addition, we also present a method of cascading LPFGs with different periods to expand the operating bandwidth.

2. Investigation of single-LPFG based mode filters

According to the mode coupling theory of LPFGs, the fundamental mode in the fiber core will couple with a specific cladding mode when the phase matching condition is met. The relationship between the grating period Λ and the effective index of the core and the cladding modes is $\Lambda = \lambda/(n_o(\lambda) - n_c(\lambda))$, where λ is central wavelength of grating, $n_o(\lambda)$ is the effective index of a core mode, and $n_c(\lambda)$ is the effective index of a cladding mode. Therefore, the fundamental mode will couple with the cladding mode if the LPFG is written in the core. The segment of the FMF written with LPFG is generally a naked optical fiber, and the two ends of which are accompanied by FMF segments with coating. Generally, the refractive index of the coating is higher than the cladding index, therefore, the converted cladding mode will be extended to the coating of the FMF and dispelled.

It would be difficult to couple only the fundamental mode with the cladding mode in a FMF, owing to the fact that a naked optical fiber is surrounded by air, which leads to a wide range of effective indices of cladding modes. Our idea is to introduce a surrounding material with refractive index only slightly lower than the cladding index, therefore, the effective indices of the cladding modes are limited to a small range. By designing a phased-matched LPFG for the fundamental mode (LP_{01} mode) and a specific cladding mode, the fundamental mode will be coupled to the cladding mode, and finally dispelled in the segment of coated optical fiber. On the other hand, the high-order modes in the fiber core are not phased-matched with cladding modes, therefore, they can still reside in the fiber core.

The configuration is shown in Fig. 1. The FMF parameters are set as core refractive index $n_o(\lambda) = 1.46$, cladding refractive index $n_c(\lambda) = 1.45$, core diameter $d_o = 10\ \mu m$, and cladding diameter $d_c = 125\ \mu m$. The refractive index of the surrounding material is $n_t = 1.44$. The default operating wavelength is set as 1550 nm, at which the optical fiber can support the propagation of the LP_{01} and LP_{11} modes.

The LPFG is designed to couple the LP_{01} mode with the LP_{03} cladding mode. The effective indices of the modes are solved numerically by mode solution using a full vectorial finite-element method with perfectly matched layer boundary conditions [28]. The period of the LPFG is set as 200 μm based on the solution and the modulation depth of the LPFG is set as 0.001. The mode coupling characteristics of the LPFG are demonstrated by launching the LP_{01} and LP_{11} modes independently into the fiber core, and recording the mode power by using the beam propagation method [29,30]. It's well known that the LP_{01} mode will couple with the azimuthally symmetric cladding modes if the applied LPFG is also azimuthally symmetric. Partial coupling could also happen between the LP_{11} mode and the cladding mode with similar symmetry. For example, partial coupling could happen between the LP_{11} mode and the cladding LP_{1n} ($n > 1$) mode when the grating period is set to be 200 μm. The variations of the mode distribution in the LPFG are shown in Fig. 2, where L_H is coupling period of LP_{11} mode. We can see the LP_{11} mode can be converted to the cladding mode although the majority of the mode field still locate in the fiber core. It is obvious that such coupling should be avoided in order to reduce the transmission loss of the LP_{11} mode. As shown in Fig. 3(a), the normalized mode power varies with the propagation distance in the proposed LPFG. We can see the LP_{01} mode shows a strong coupling characteristic with the cladding mode, therefore, effective suppression of the LP_{01} mode can be achieved. On the other hand, the LP_{11} mode also shows a slightly power variation, which means that partial coupling between the LP_{11} mode and the cladding modes happens. It is not a surprising result. As there are still a large number of the cladding modes, even if the high-order mode and the cladding modes do not meet the phase matching condition, partial coupling could happen. Just as expected, partial coupling leads to shorter coupling period as compared to the phase-matched coupling [21,22,24–26]. The suppression of the coupling between the LP_{11} mode and the cladding modes can be achieved by increasing the effective index difference between the LP_{01} and LP_{11} modes, and meanwhile, reducing the span range of the effective indices of the cladding modes by narrowing the refractive index difference between the cladding and the surround material. In addition, in this article we will explore the suppression of the high-order mode coupling by using an apodized LPFG.

As mentioned before, the coupling period of partial coupling is shorter than that of phase-matched coupling. Also the amplitude of coupling is associated with the modulation depth of the grating. Therefore, we can apply an apodized LPFG so that the LP_{01} mode can still be converted to the cladding mode, whereas the LP_{11} mode will have weak coupling with the cladding modes at the two ends of the LPFG, owing to the lower modulation depth at the two ends of the LPFG. The modulation amplitude of the LPFG along the propagation direction is set as $v(Z) = \cos(\pi Z/L)$, with $-L/2 < Z < L/2$ and L is length of the LPFG. The length of the LPFG is determined to be 18 mm, which ensures the LP_{01} mode be converted to the cladding LP_{03} mode completely. The length of the LPFG is longer than that of the uniform LPFG, the reason is that its overall modulation depth is lower than that of the uniform LPFG. So it would need longer length to realize the conversion. Fig. 3(b) shows the results of the apodized LPFG, the LP_{01} mode shows similar characteristics with the uniform LPFG, whereas power transferring of the LP_{11} mode is effectively suppressed. Even though there is still coupling at the middle of the grating, owing to the higher modulation depth at the position, but the power will transfer back, and lead to low loss at the output port.

Mode filter should work with sufficiently large bandwidth. Since the LP_{01} mode to be filtered in a few-mode optical fiber is generally a residual mode, the mode filter do not need high enough suppression ratio. For example, a conversion efficiency of 10 dB for a mode converter means that the power loss of the converted mode is lower than 0.5 dB which is low enough for the converted mode but the cross-talk should be improved. Therefore, if a mode filter is applied, an insertion loss of 10 dB is large enough to suppress the LP_{01} mode to better than 20 dB. Based on such consideration, the operating wavelength range is defined by the requirement of the output power of the LP_{01} mode less than 10%, that is, the device loss of the LP_{01} mode is higher than 10 dB. Normalized output powers as functions of wavelength for the proposed optical fiber with the apodized LPFG are plotted in

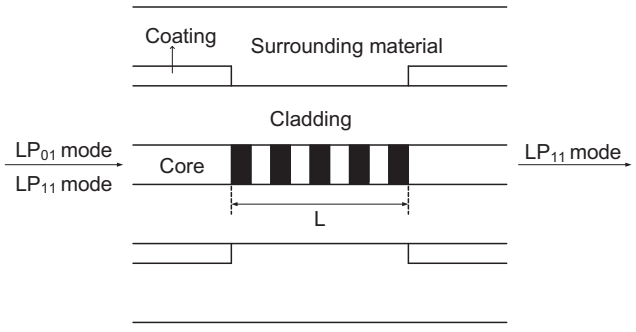

Fig. 1. The configuration of the mode filter based on a single LPFG.