LONG-PERIOD GRATING DEVICES FOR APPLICATION IN OPTICAL COMMUNICATION

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ABSTRACT

We present a review of the development of long-period fiber grating devices for application in optical communication. The recent studies on the realization of long-period gratings in optical planar waveguides are also highlighted.

Keywords: Fiber gratings, optical communication, optical devices, optical waveguides, waveguide gratings.

1. INTRODUCTION

A grating formed in an optical fiber or waveguide to achieve light coupling between two co-propagating modes usually requires a grating pitch in the range from several micrometers to several millimeters, which is much longer than that required for a Bragg grating. Therefore, this kind of grating is generally referred to as the long-period grating (LPG).

LPGs differ from each other in the types of modes involved in the coupling process. The earliest demonstration is a polarization coupler [1], where a birefringent fiber is stressed periodically once per beat length, so that the two polarization modes of the fiber are coupled efficiently at a specific wavelength. Similar coupling effects have been observed by setting up an acoustic grating along a birefringent fiber [2]. More often, LPGs are designed to couple light between two guided modes of a few-mode fiber [3]-[5]. For example, by guiding an acoustic flexural wave along a fiber, efficient mode coupling between the LP_{01} and LP_{11} modes has been demonstrated [3]. Such an acousto-optic grating has found many applications as a tunable filter. By tailoring the dispersion properties of few-mode fibers, many useful LPG devices can be made [5].

The most influential development in LPGs is perhaps the demonstration of efficient coupling between the guided mode and the cladding modes of a single-mode fiber by using an LPG [6]. Nowadays, long-period fiber gratings (LPFGs) usually refer to this class of LPGs. Because cladding-mode LPFGs do not need any special means to separate the coupling modes, their deployment for various applications is quite simple. The availability of a large number of cladding modes also offers flexibility in filter design. This paper reviews mainly the development of this class of gratings for application in optical communication. It should be mentioned that LPFGs have also found many applications in optical sensing [7].

Grating structures are important not only in fiber optics but also in integrated optics. Static and dynamic waveguide gratings for light coupling between the TE and TM modes of planar waveguides have been demonstrated for a long time [8]. Because waveguides can be fabricated into different shapes and with different materials, they offer much higher flexibility in the design of optical devices than fibers. Recently, cladding-mode LPGs in waveguides, known as long-period waveguide gratings (LPWGs), have been proposed [9] and demonstrated [10]. Using suitable polymer materials, LPWGs can provide a superior wavelength tuning capability. The more important works on LPWGs are also highlighted in this paper.

2. GENERAL CHARACTERISTICS

The transmission characteristics of an LPG, whether formed in a single-mode fiber or waveguide, can be analyzed by the coupled-mode theory [6],[9]. There exists a specific wavelength (resonance wavelength), at which the coupling between the guided mode and a specific cladding mode is strongest. The transmission spectrum of an LPG usually consists of a number of rejection bands centered at resonance wavelengths that correspond to different cladding modes. The center wavelength of a rejection band is in general sensitive to a number of physical parameters (temperature, strain, external refractive index, fiber/waveguide dimensions, grating pitch, etc.) and its sensitivity depends critically on the dispersion properties of the modes [11],[12]. This property of the LPG has been explored for the realization of tunable devices and sensors. The bandwidth of a typical centimeters-long LPG is of the order of 10 nm. The bandwidth can be increased significantly by manipulating the dispersion properties of the modes. To obtain more sophisticated transmission characteristics, one can vary the coupling coefficient (apodization) and the pitch (chirping) along the grating [13], or introduce phase shifts along the grating [13],[14]. A transfer-matrix method has been demonstrated for the analysis of complicated grating profiles [13],[14]. A perturbation theory has also been developed for the analysis of the sensitivity characteristics of LPFGs [15].

3. LONG-PERIOD FIBER GRATINGS

3.1 Fabrication

The fabrication of an LPFG relies on the introduction of a periodic modulation of the optical properties of the fiber, which can be in the form of index modulation along the fiber core [6] or physical deformation along the fiber [7]. The most widely used method of introducing an index modulation is by UV irradiation using wavelengths between 193 and 266 nm. Index modulation can be produced point-by-point along a UV-photosensitive fiber or by having a length of the fiber exposed to the UV light through an amplitude mask [6],[16]. Index modulation has also been achieved by ion implantation [17], near-infrared femtosecond pulse irradiation [18], CO_2-laser irradiation [19],[20], mechanical stress relaxation [21], and electrical discharges [22]. Structural deformation of the fiber has been demonstrated by using mechanical apparatus [23], tapering the fiber [24], or deforming the the cladding [25]. Dynamic gratings with controllable transmission characteristics have been implemented by using coil heaters [26], acousto-optic modulation [27],[28], mechanical loading [29]-[32], and liquid-crystal filled hollow-core fibers [33]. In general, it is not difficult to produce a rejection band with a contrast of 20 – 25 dB by using most of the aforementioned methods. High-precision point-by-point writing using finely controllable stable irradiation, such as high-frequency CO_2-laser pulses [20], is capable of producing a much larger contrast [34].

For gratings written by the UV-irradiation methods, because the index change is uniform across the core, the LP_{01} mode is coupled only to the cladding modes with the same symmetry, namely, the LP_{0m} ($m \geq 2$) modes. For gratings written by methods that create an asymmetric index distribution across the fiber cross-section, such as the CO_2-laser irradiation methods [19],[20] and the mechanical-loading methods [29]-[32], the LP_{01} mode can be coupled to a larger number of modes, including those that do not possess circular symmetry. It seems that this observation has been overlooked by some studies [31],[32]. In addition, mechanical loading methods can introduce significant birefringence in the fiber and, as a result, produce a transmission spectrum that is highly polarization sensitive [29],[32].

3.2 Applications

3.2.1 Optical filters

The resonance wavelength of a typical LPFG shifts by only 3 to 10 nm for a change of 100 °C. By carefully choosing the order of the cladding mode and using a photosensitive B-Ge co-doped fiber, a tuning range of 27.5 nm with a temperature control of 10 °C has been obtained [35]. Recoating an LPFG properly can provide a tuning range of 50 nm with a temperature control from 20 to 80 °C [36]. The use of a microstructured fiber filled with polymer [36] or liquid crystal [37] can give comparable performance [36]. Electrical tuning has also been achieved with metal-coated gratings [38]-[40]. A metal-coated grating written in a polymer-filled air-clad fiber offers a tuning range of 60 nm with a tuning efficiency as high as 320 nm/W [40].

It is possible to tune the resonance wavelength by etching the cladding of the fiber and/or changing the refractive index of the surrounding medium [41],[42]. A reduction of 1 μm in the cladding diameter shifts the resonance wavelength towards the shorter wavelength by as much as ~20 nm [41]. Tensioning and bending of an LPFG can also change both the resonance wavelength and the contrast of the rejection band, which is, in fact, the basic principle for many sensing applications [7].

An LPFG bandpass filter has been demonstrated by darkening the fiber core in the middle section of an LPFG with a focused UV beam [43] or by insertion of a section of a hollow-core fiber between two identical LPFGs [44]. Introducing π-phase shifts along an LPFG also results in special bandpass filters [13],[14], which have found applications in actively mode-locked fiber ring lasers [45]. High-performance π-phase-shifted LPFGs can be produced by point-to-point inscription with an electric-arc writing technique [46].

LPFGs can also form multi-port couplers. It has been demonstrated both theoretically and experimentally that the light energy coupled to the cladding mode can be collected by using two parallel LPFGs [47],[48]. The transmission spectra from the two parallel gratings are complementary to each other, one showing band-rejection characteristics and the other showing bandpass characteristics. The structure of two parallel LPFGs thus operates as an all-fiber broadband add/drop multiplexer and has potential applications in WDM systems. Recently, a broad-band optical coupler based on three parallel identical LPFGs has been demonstrated [49]. A total power transfer efficiency of 85% at the resonance wavelength has been achieved. Other implementations include placing a tapered fiber in parallel to an LPFG [50] and writing an LPFG in a two-core fiber with slightly different cores [51].

The structure of two cascaded LPFGs has been demonstrated as a multi-channel filter for multi-wavelength signal generation in WDM systems [52]. The transmission spectrum of the filter has a sinusoidal fringe pattern with an envelope governed by the shape of the rejection band of the individual grating [53] and the channel spacing can be controlled by changing the physical separation of the two gratings [13],[53]. A technique of generating high-repetition-rate pulses based on cascaded LPFGs has also been demonstrated [54].

When an LPG is written in a birefringent fiber, two resonance dips appear in the transmission spectrum, which correspond respectively to the two principal polarizations of the fiber. Such a grating has been used to realize a wavelength-selective fiber polarizer [55]. An extinction ratio >30 dB and an insertion loss < 0.5 dB have been achieved. LPFG polarizers have also been implemented with few-mode fibers [56]. Using the polarization-dependent spectrum of an LPFG, a wavelength-switchable erbium-doped fiber ring laser has been demonstrated, where dual-wavelength operation is accomplished by rotating the polarization plane of the fiber laser cavity [57].

3.2.2 Gain flatteners for optical amplifiers

LPFG filters can be considered as wavelength-selective attenuators and therefore used as gain flatteners for erbium-doped fiber amplifiers (EDFAs) [58],[59]. By careful control of the filter spectrum and fiber length, the EDFA gain has been flattened to within 1 dB over 40 nm while producing a noise figure below 4.0 dB and an output power of nearly +15-dBm [59]. Another method of achieving broad-band gain flattening is to use a phase-shifted LPFG [60]. To flatten a gain spectrum that contains several peaks, a compact module based on using different cladding modes of a number of concatenating LPFGs has been proposed [61]. More recently, an EDFA gain spectrum flattened to within 0.35 dB over 30 nm has been realized by using an optimized design of step-changed LPFGs [62]. Other gain-flattening schemes include etching [63] and UV trimming [64] of LPFGs. Dynamic gain flattening has been demonstrated with bending of two cascaded gratings [65], or twisting of a grating [66],[67].

3.2.3 Fiber coupling

Fiber-to-fiber coupling via the cladding mode of the fiber can relax the alignment tolerances substantially [68],[69]. A lens-free fiber-to-fiber connector that has a long working distance and a wide alignment tolerance has been implemented by using two matched LPFGs written in a double-cladding fiber [70]. Lateral alignment tolerances of ~450 μm and ~3 mm for coupling losses less than 1 dB and 3 dB respectively have been achieved. Laser-to-fiber coupling based on an LPFG and a lens has also been demonstrated [71]. A working distance longer than 100 μm and a lateral tolerance of 2.5 μm have been obtained [71]. Fiber-to-waveguide coupling has also been demonstrated with a CO_2-laser-induced LPFG [72], which does not require access to the fiber and waveguide end faces.

3.2.4 Dispersion compensation

LPGs in dispersion-tailored few-mode fibers have been employed in dispersion compensation. Higher-order mode (HOM) dispersion compensation using the LP_{02} mode can offer dispersion-slope matching to practically any transmission fibers [73]. An HOM fiber having a propagation loss of 0.44 dB/km and a dispersion coefficient of −210 ps/nm/km has been fabricated [74]. Using the HOM dispersion-compensation scheme, a 40-Gb/s hybrid Raman/erbium-amplified system with a transmission distance of 1700 km has been demonstrated [75]. A tunable dispersion compensator that utilizes an HOM fiber and switchable LPGs has also been made, which provides a dispersion tuning range of 435 ps/nm over a bandwidth of 30 nm [76].

4. LONG-PERIOD WAVEGUIDE GRATINGS

To eliminate the geometry and material constraints of LPFGs, LPWGs have been proposed [9]. The theoretical studies based on a slab waveguide model [9],[77] show that the transmission characteristics of an LPWG depend critically on the physical dimensions of the waveguide. Since the core and the cladding dimensions of a waveguide can be controlled easily, LPWGs should offer higher flexibility in the filter design than LPFGs, especially in the design of tunable devices.

Over the last few years, there has been significant progress in the realization of LPWGs with different waveguide structures and different materials. LPWGs have been demonstrated with polymer-clad ion-exchanged glass waveguides [10], all-polymer channel waveguides [78],[79], ridge waveguides [80], and rib waveguides [81]. Many of these LPWGs [10],[78]-[80] provide linear wavelength tuning over the (C+L)-band (from 1520 to 1610 nm) with a temperature control of less than 30 °C. By releasing the stress in an all-polymer LPWG through etching of the cladding width, a filter with a polarization-insensitive resonance wavelength thermal-tunable over the (C+L)-band with a temperature range of only 8 °C has been achieved [78]. The temperature sensitivity of an LPWG is particularly sensitive to the cladding thickness of slab and ridge waveguides [80], while it is more sensitive to the core size of a channel waveguide [79]. An LPWG has also been fabricated on a glass channel waveguide by a double ion-exchange process [82], where the grating is formed by varying the width of the core periodically along the waveguide. Because the waveguide structure and the material are similar to those of a fiber, the grating shows a temperature sensitivity of only ~1 pm/°C.

The conventional fabrication process based on photolithography and reactive-ion etching (RIE) is slow and expensive. Recently, a nano-imprint lithography technique has been demonstrated for the fabrication of an LPWG in a rib waveguide [83]. This technique is simple and low-cost, and can be further developed for mass production of LPWGs. A direct UV-writing technique based on a 248-nm KrF excimer laser has also been demonstrated for the fabrication of LPWGs in polymer waveguides [84]. This technique is practically the same as the UV-irradiation technique for the fabrication of LPFGs. It allows in-situ monitoring of the growth of the transmission spectrum of an LPWG and thus relaxes the fabrication tolerances.

All the LPWGs described above are permanent gratings. An electro-optic LPWG with a reconfigurable transmission spectrum has been proposed and studied theoretically [85]. Experimental implementation is yet to be demonstrated. An easier way to make a dynamic LPWG is by using the large thermo-optic effect in polymer material, where the grating is induced thermally by applying current to an electrode grating deposited on a polymer waveguide [86]. In fact, a waveguide filter with two vertically stacked thermally-induced gratings has been implemented [87]. The transmission spectrum of this filter can be adjusted dynamically by controlling the electric powers applied to the two electrode gratings. Most recently, a more power efficient metal-grating filter with both widely tunable center wavelength and contrast has been demonstrated [88]. The contrast of the rejection band can be tuned by 28 dB with 45-mW electric power applied to the metal grating and the center wavelength can be tuned over the (C+L)-band with a temperature control of 40 °C. Dynamic LPWGs can find applications as tunable notch filters, polarization-dependent loss compensators, or variable attenuators.

In order to generate more sophisticated transmission characteristics, the idea of post-processing the profile of the waveguide cladding along a uniform LPWG has been suggested [89]. In practice, the waveguide cladding can be trimmed by using the conventional etching technique [90] or the UV-irradiation technique [91]. To further increase the functionality of LPWGs, a polymer LPWG bandpass filter has been fabricated, which consists of two identical gratings separated by a gap to block the light at off-resonance wavelengths from passing through [92]. The structure of two parallel LPWGs for the realization of a broadband add/drop multiplexer has also been studied [93]. The use of parallel LPWGs has the clear advantage over parallel LPFGs in device packaging. It is also easy to form multi-port couplers and add/drop multiplexers with LPWG arrays.

5. CONCLUSIONS

Long-period fiber grating (LPFG) has been considered as a distinct field of study (like fiber Bragg grating) only for the past ten years, i.e., since the cladding-mode LPFG was proposed, regardless of the fact that many LPGs in different forms had been studied much earlier. In terms of application, the cladding-mode LPFG has two distinct advantages, compared with other types of LPGs (e.g., polarization converters, acousto-optic filters, few-mode fiber gratings). First, it does not require any other component like polarizer or mode converter to separate the coupling modes. It can just be used as it is and thus simplifies its deployment, especially in systems where many gratings are needed. Second, the light that is coupled to the cladding of the fiber is no longer shielded from the fiber and becomes sensitive to any changes in the surrounding medium. This property opens up many new possibilities for various applications (e.g., fiber-to-fiber coupling, add/drop multiplexing). The potential for the development of new devices through the manipulation of the cladding modes is large. Long-period waveguide grating (LPWG) is an emerging field. LPWGs share many of the key features of LPFGs, yet enjoy the flexibility offered by the optical waveguide technology. It is envisaged that the activities in the development of LPWG-based devices to provide new functions will continue to grow.

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