Tunable optical fiber devices based on broadband long-period gratings and pumped microfluidics

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(Received 19 June 2003; accepted 8 October 2003)

This letter describes classes of tunable microfluidic fiber (μFF) devices that use specially designed long-period gratings in which the phase matching condition is satisfied over a wide spectral range. Dynamic tuning is achieved by electrowetting-based pumping of microfluidic plugs back and forth over the gratings. As specific examples, we demonstrate dynamically tunable broadband attenuators and filters with adjustable profiles by using fluids with different refractive indices. These devices have attractive features that include in-fiber design and polarization-independent behavior together with low-power, nonmechanical, fully reversible, and latchable tuning. © 2003 American Institute of Physics. [DOI: 10.1063/1.1633331]

Tunable optical fiber devices are emerging as valuable components of high-speed optical communications systems. Long period gratings (LPGs), which couple the fundamental core mode to higher order copropagating cladding modes, have been studied extensively because of their potential applications in band rejection, and gain control. We recently demonstrated that microfluidics actuated by electrowetting effects provides a convenient means to tune the optical properties of these and other fiber structures. These microfluidic fiber (μFF) devices offer low power operation and a rich range of tuning mechanisms. A drawback of μFF devices that use conventional LPGs, however, is that the tuning range is typically only a few nanometers, primarily limited by the bandwidth of the LPGs. Although LPGs based on large index variations, induced by microbending of fiber, yield relatively large bandwidth (~30 nm for 20 dB mode conversion) they suffer from polarization dependent characteristics, and high insertion losses (~0.4 dB). Recently, we showed that with specially engineered few-mode fiber it is possible to achieve a turn around point (TAP) in the LPG phase matching condition, which yields a wide bandwidth (20 dB coupling over 63 nm), low loss, and polarization independent performance with only modest index variations. In this letter, we combine μFF designs and TAP LPGs to build a class of fiber device that provides continuously tunable attenuation and spectral reshaping over a large bandwidth. The transmission characteristics of these μFF devices are controlled by pumping fluids with different refractive indices around the TAP LPG by use of electrowetting pumps and planar microfluidic networks. These devices have low power, latchable operation with polarization independent and low loss behavior over a wide wavelength range.

In LPGs, the spectral dependence of the resonant coupling is primarily determined by the difference in the effective indices between the two coupling modes (Δn) and the difference in their corresponding group indices (Δn_g) and is given by:

$$\frac{d\Lambda}{d\lambda_{\text{res}}} = \frac{\Delta n_g}{\Delta n^2},$$

where λ_{res} is the resonant wavelength and Λ is the grating period. Conventional LPGs exhibit strong mode conversion at a specific resonant wavelength, with near-monotonic decrease in coupling over bandwidths of 3–5 nm. If a fiber is designed such that one of the higher order cladding modes transitions, as a function of wavelength, from being localized primarily in the fiber cladding to a spatial profile involving significant overlap with the surroundings, a unique feature results in the phase matching curve (plot of grating period versus wavelength). This mode transition leads to matching of the group indices of the fundamental and the higher order cladding mode, which in turn makes Δn_g = 0, thus leading to a maxima (called TAP, henceforth) in the phase matching curve. The resulting spectrum has a wide bandwidth and is extremely sensitive to the optical properties of the surroundings. The extreme sensitivity has, for example, recently demonstrated to yield more than 25 dB amplitude modulations with external index modulations of only 10^{-4}.

Figure 1(a) shows simulated phase matching curves for a LPG, with a period of 150 μm and UV induced refractive index gradient Δn=1.54×10^{-3}, in a fiber engineered to possess a TAP in ambient refractive index n=1.39 at 1530 nm. The figure also depicts the phase matching curves for the same grating in surroundings with different refractive indices (n=1.33 and n=1.41). When the index is higher than 1.39, the phase matching condition is satisfied at two different wavelengths [indicated by arrows in Fig. 1(a)] splitting the...
that a grating period of 150 μm depicted by symbols in Fig. 1 matching curve at this wavelength in silicone oil. The curves covered with silicone oil a wavelength of fundamental core mode and the LP012 cladding mode such written into specially designed optical fibers that support the experimental demonstration of this effect, we used gratings show the corresponding simulated transmission spectra. For propagating cladding modes. The solid lines in Fig. 1 diminished coupling between the core mode and the co-index is lower than 1.39, the phase matching condition is no spectrum into two LPG-like resonance features. When the index is lower than 1.39, the phase matching condition is no longer satisfied at any wavelength and, as a result, there is diminished coupling between the core mode and the co-propagating cladding modes. The solid lines in Fig. 1(b) show the corresponding simulated transmission spectra. For experimental demonstration of this effect, we used gratings written into specially designed optical fibers that support the fundamental core mode and the LP012 cladding mode such that a grating period of 150 μm couples these two modes at a wavelength of ~1530 nm. The thickness of the cladding is then reduced by etching in hydrofluoric acid so that the LP012 mode makes a transition from the cladding to the surroundings above this wavelength when the grating is fully covered with silicone oil (polydimethylsiloxane, DMS-T02, Gelest, Inc, n = 1.39), i.e., a TAP is achieved in the phase matching curve at this wavelength in silicone oil. The curves depicted by symbols in Fig. 1(b) show the spectra when the grating is immersed in three different fluids: silicone oil, water (n = 1.33) and 41% aqueous solution of sodium dichromate (n = 1.41). As predicted by the simulation, the grating optimized for TAP in silicon oil shows splitting (broadband attenuation) when immersed in fluid with higher (lower) refractive index than that of silicon oil. We note that the resonance feature does not completely disappear even when the TAP grating is fully immersed in water and shows an ~3 dB insertion loss. This loss is associated with the fact that the refractive index of water is slightly higher than that is needed for the grating optimized for TAP in silicone oil. An optimized refractive index combination of two fluids shows a near perfect disappearance of the resonance feature. Thus, by covering the grating structure with fluids with different refractive indices, it is possible to switch the optical transmission characteristics of the grating between the TAP splitting and TAP-attenuation states. We exploit these TAP LPG effects with an integrated microfluidic network and electrowetting pumps to form a μFF device that offers a variety of broadband, continuously tunable optical characteristics.

Figure 2 shows a schematic view of the three components of the microfluidic part of the device: an insulating spacer that has micromachined channels for confining the motion of the fluids and two glass substrates with patterned indium tin oxide (ITO) electrodes that provide the electrowetting pumps. The white lines on the top and bottom electrode substrates separate the electrodes from the rest of the substrate, which is electrically grounded. By swapping V1 and V2 between zero and positive potentials the conductive fluid can be pumped into and out of overlap with the fiber grating. The inset shows three snapshots of the section of the μFF device as the conducting fluid advances over the TAP grating.
The intensity, $I$, can be written as:

$$I = 1 - k^2 \frac{\sin^2 \left[ \sqrt{\kappa^2 + \delta_1^2} \right]}{\kappa^2 + \delta_1^2} - k^2 \frac{\sin^2 \left[ \sqrt{\kappa^2 - (\delta_2^2)} \right]}{\kappa^2 + \delta_2^2},$$

where $L$ is the total length of the grating, $\kappa$ is its coupling coefficient (proportional to the induced index change), $I$ is the length, and $\delta_1$ is the detuning associated with the part of the grating immersed in one of the fluids, while $\delta_2$ is the detuning associated with the grating immersed in the other fluid. The detuning coefficient $\delta$ is defined as $\delta = 2\pi/\Lambda - (\beta_1 - \beta_2)$ with $\Lambda$ being the grating period and $\beta_1$ and $\beta_2$ being the respective propagation constants of the fundamental core mode and the LP0_{12} core mode. The solid line represents the theoretical fit to the experimental data using Eq. (1). This simple model yields reasonably good agreement with the experimental results.

For another demonstration of a TAP LPG-based $\mu$FF device, we used the chromate solution, which has higher refractive index than that of silicone oil, as the conducting plug to induce and tune a split spectrum using the same TAP grating. Figure 4 shows the spectrum splitting into two separate features as the degree of overlap increases. The spacing between the resonant wavelengths i.e., the separation between the two wavelengths indicated by arrows in Fig. 4 increases with increase in the overlap of the fluid over the grating. A system with higher refractive index will produce sharp resonance features, each of which can potentially be used as a narrow band filters.

This concept can be extended to multiple fluids with different refractive indices for dynamically switchable attenuation, splitting, and superstructures, etc. These and related $\mu$FF devices have numerous potential applications in optical communication system.

This research was supported in part by the NSF GOALI Grant.