Tunable microfluidic optical-fiber devices

Improvements in transmission speeds and capacities of lightwave communication networks typically follow from advances in optics and, often, from progress in the materials science and physics of the optical fiber that forms the backbone of these systems. There are tremendous potential applications of fiber-based devices that can modify, dynamically, the characteristics of optical signals as light passes through the fiber. Many important network operations can be performed in this manner: dynamic chromatic dispersion compensation, programmable adding and dropping of wavelength channels, dynamic gain equalization, and so forth. Tunable fiber devices naturally incorporate the attractive features of optical fiber (i.e. low cost, polarization-independent behavior, etc.) and the well-developed techniques for fiber manipulation (i.e. splicing, terminating, etc.). They also avoid many of the disadvantages—difficult alignment tolerances, challenging reliability requirements, optical coupling inefficiencies, etc.—of components that use bulk optics, waveguides, or microelectromechanical systems, each of which requires light to be coupled out of and back into a fiber.

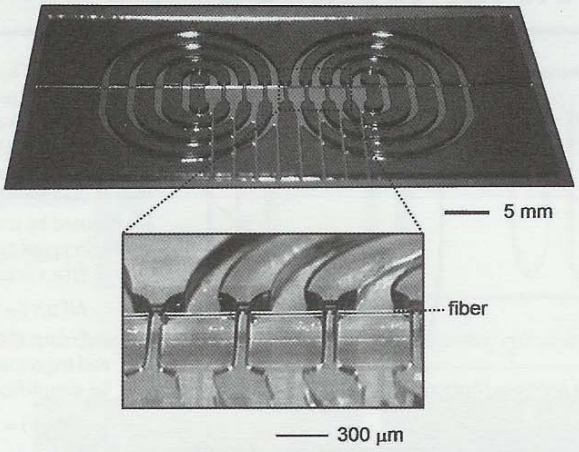

Figure 1. Microchannel structure for a digitally-tunable microfluidic optical fiber device (top). The system consists of eight independent racetrack channels and a mounting slot for the fiber (bottom).

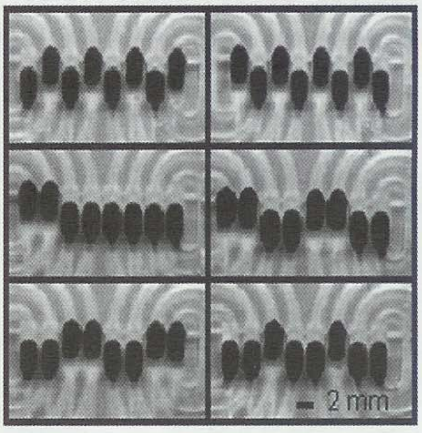

Figure 2. Top view micrographs of a digitally-tunable microfluidic optical fiber device in various tuning states. Electrowetting pumps drive the dark fluidic plugs into or out of overlap with the fiber.

Existing tunable fiber devices rely almost exclusively on simple thermo-optic and strain-optic effects. The recent introduction of pumped microfluidics into this area provides broad and flexible tuning possibilities.[1,2] This type of photonic device, known as a microfluidic optical fiber (μFF), uses fluidics to manipulate the transmission characteristics of fiber segments whose propagating or leaky modes are sensitive to the optical properties of its surroundings (i.e. the fluids in this case). The μFF devices provide many features—low power, non-mechanical operation, wide tuning range, low insertion loss, polarization independent behavior, etc.—that are attractive for applications in optical networking. A representative μFF design uses planar microfluidic channels that incorporate optical fibers.[2]

Electrowetting phenomena—in which the contact angle of a conductive fluidic droplet can be reversibly adjusted by application of an electrical voltage—can be exploited to move microfluidic plugs into or out of overlap with the fiber. Pumps based on electrowetting provide low-power operation, relatively fast pumping speeds, and latchable operation with only a pair of electrodes per pump and no moving parts. In one class of device, a set of discrete microfluidic plugs are individually pumped into or out of overlap with a segment of fiber in a digital manner. Figure 1 shows eight molded plastic recirculating 'racetrack' channels to define the flow paths. The fiber mounts into a slot perpendicular to the flow direction. A separate substrate that supports the electrowetting pumps seals against the top surface of the bottom substrate to complete the device. The pumped fluid plugs reside in the short, widened regions of each racetrack.

The electrowetting pumps provide independent control over the positions of the eight plugs (black, as shown in Figure 2). In the up position, the plugs overlap the corresponding segment of optical fiber. In the down position, they are completely out of overlap. Interaction of the plugs with the fiber modifies the transmission characteristics of an in-fiber long-period grating (LPG) designed to create a narrow-band attenuation. In particular, overlap of index matching fluids decreases the strength of this attenuation by an amount proportional to the degree of overlap (i.e. the number of plugs in this case). Figure 3 shows transmission spectra recorded as the number of overlapping plugs increases from one to eight. The different tuning states are achieved reproducibly, in a digital manner, with a switching speed of ~70ms.

One possible application is for dynamic gain equalization (DGE) in wavelength-division-multiplexed communication systems. In this case, a cascaded array of these tunable narrowband filters forms a complex, tunable filter shape that can be adjusted (dynamically) to offset wavelength- (and time-) dependent variations in signal amplification and loss experienced by light passing through the network. Similar fluidic concepts can be used in grating light modulators, lenses, waveguides, and other components.[3-6] This wide range of applications creates interest in pumped microfluidic systems

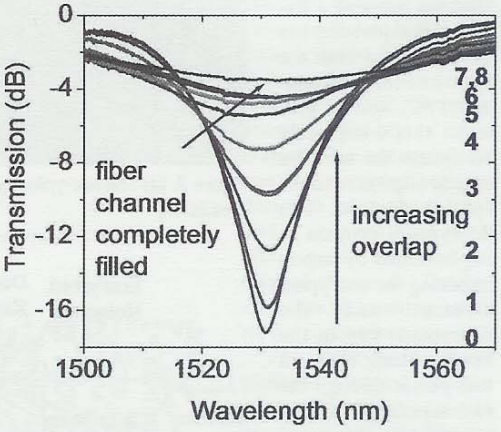

Figure 3. Transmission spectra of a long-period grating (LPG) as eight index-matched fluidic plugs are pumped into overlap with the fiber, sequentially starting with a plug at the edge of the grating (top). The numbers on the right indicate the number of plugs that overlap the grating.

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Simple optical decryption based on a modified joint-transform correlator technique

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$f(x,y)$ and the correlator were simulated to generate the encrypted hologram, while the decryption key $G(u,v)$ was experimentally shown to recover the encrypted information. The encoded hologram and the decrypted image are shown in Figure 2 (a) and (b) respectively. Using the optical setup shown schematically in Figure 3, the encrypted image was recovered with the decryption key.

For the fabrication of the elements, the number of sampling points was again chosen to be 128×128. Each pixel was 8×8μm for both holograms, giving a total size of 1.024×1.024mm. The holographic patterns were transferred onto pieces of quartz coated with MMA (methyl methacrylate) using electron beam lithography (EBL).

The decoded image is shown in Figure 4: the original image is recovered clearly using the optical decryption key. In the figure, the bright on-axis spot corresponds to the 0^{th}-order diffraction component.

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Tunable microfluidic optical-fiber devices

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for optics, and suggests a bright future for this emerging field of technology.

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Design of distortion-invariant optical ID tags

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output plane of the recognition system along with the decoded signature obtained for a rotated (80°) and scaled version (scale factor 0.7) of the ID tag shown in Figure 1(c). The signature was correctly decoded and identified using nonlinear correlation. To demonstrate the robustness of the ID tags for verification and identification, we recovered the decrypted information from a rotated (40°) and scaled (0.8 scale factor) ID tag, and decrypted the encoded information using a false phase key. In this case, we obtained a noisy image with no recognizeable signature: See Figure 2(b).

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An input phase mask designed for optical space bandwidth

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