Coated fiber tips for optical instrumentation

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ABSTRACT

Compact optical systems can be fabricated by integrating coatings on fiber tips. Examples include fiber lasers, fiber interferometers, fiber Raman probes, fiber based spectrometers, and anti-reflected endoscopes. These interference filters are applied to exposed tips – either connectorized or cleaved. Coatings can also be immersed within glass by depositing on one tip and connecting to another uncoated tip. This paper addresses a fiber spectrometer for multispectral imaging - useful in several fields including biomedical scanning, flow cytometry, and remote sensing. Our spectrometer integrates serial arrays of reflecting fiber tips, delay lines between these elements, and a single element detector.

Keywords: Coated fiber tips, optical instrumentation, multispectral scanning

1. INTRODUCTION

The tips of optical fibers can be coated with interference filters to enable compact optical instruments. Potential applications include fiber lasers, fiber interferometers, fiber Raman probes, fiber based spectrometers, and anti-reflected endoscopes.[1,2,3,4] Many fiber configurations are applicable, including single and multimode designs. These interference filters are applied to exposed tips – either connectorized or cleaved. Coatings can also be immersed within glass by depositing on one tip and connecting to another uncoated tip. Angles of incidence at the coatings, related to various modes in a fiber, must be considered when designing applications. Our labs have shipped coated fiber tips for many of these applications - including edge filters, band pass filters, and antireflection coatings. As an example, this paper addresses a fiber spectrometer for multispectral imaging.[5] Typically, strong signals and/or long integration times allow pixel arrays and gratings to provide quality images in many color bands. Our spectrometer uses serial arrays of reflecting fiber tips, delay lines between these elements, and a single element detector. This approach merges fast spectroscopy with standard spatial scanning to create datacubes of weak signals in real time. Each spectrum is acquired in a few microseconds. These attributes are critical during real-time applications such as in-vivo imaging or flow cytometry. The spectral band count, spacing, and width are adaptable to a given application. The following sections describe techniques for designing, fabricating, testing, and implementing coated fiber tips for our multispectral imaging system.

2. DESIGNS

Edge filters that transmit at wavelengths longer than a transition wavelength are called long pass filters. In this paper, long pass filters are used to reflect wavelengths below the transition wavelength. These edge filters are based on a sequence of high index and low index layers. A perfect filter would reflect 100% up to the transition wavelength, and then steeply descend to reflectance levels near zero at longer wavelengths. A sequence of quarter wave layers would cause non-zero oscillations at wavelengths above the transition. The oscillations are suppressed by using fractional quarter wave layers. The steepness of the descent is also dependent on the angle of incidence at the filter. In applications involving fiber tips, the angle of incidence is related to the fiber's numerical aperture. Typical single mode fibers have a numerical aperture (NA) of 0.1, an external maximum coupling angle of 5.7 degrees, and a maximum internal propagation angle of about 4 degrees. Multimode fibers have NA of up to 0.48, an external maximum coupling angle of 28.7 degrees and a maximum internal propagation angle of about 19 degrees. In multimode fiber, the internal

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angles of incidence at a fiber tip are also dependent on which modes are populated (lower order modes propagate at lower angles within the core). Figure 1 shows modeled reflectance curves at 0, 10, 15, and 20 degrees for the edge filters used in this paper.

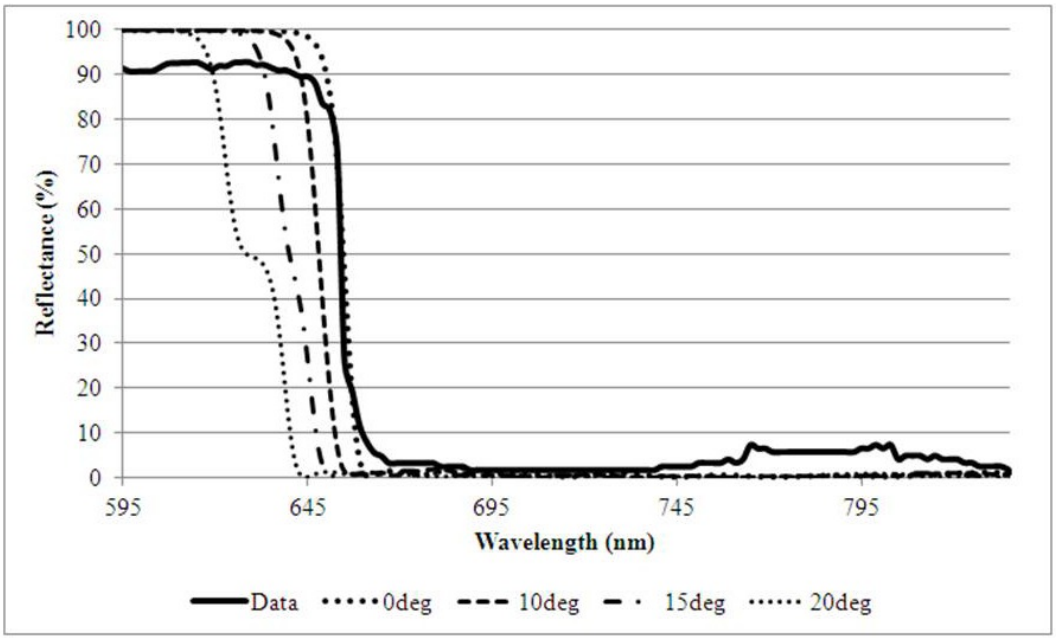

Figure 1. Reflectance of an edge filter – models at four angles of incidence and data from a coated fiber tip

Our fiber based multispectral imaging system has been described previously,[6] and is shown in more detail in figure 2. Excitation is provided by a pulsed 488 nm or 405 nm laser beam, which propagates through the spatial scanners towards the tissue sample. As the two mirrors are scanned in an x-y raster pattern, the focused spot on the sample is always conjugate with the entrance face of the multimode fiber that is connected to the beam splitter assembly. Since fluorescence from biological materials typically occurs within 1 to 5 nsec after excitation, both reflected and photoexcited signals propagate back to the fiber entrance face before the mirrors can move appreciably. This allows the mirrors to de-scan back-propagating photons such that light from the focused spot indeed stays conjugate with the fiber. As a result, scanning confocal systems can generate maps (or "images") with spatial resolution at or near the laser spot size. In this system, the 488 nm laser is focused at NA = 0.24 to a 1.2 micron diameter spot and scanned over an adjustable field (that can be zoomed from 50 to 500 microns). Since the scanning process actually generates a spatial convolution of the focused spot with features in the sample, it is possible to detect features below the diffraction limit (though they appear equal in size to the spot). The system depicted in figure 2 performs microscopy when a sample is placed at the focus of the objective lens, and endoscopy when the proximal end of an endoscope is placed in the same location. For endoscopy, a coherent fiber bundle with 30,000 three micron diameter fibers is placed under the lens. The confocal scanner raster scans the proximal end of the endoscope. A given fiber within the bundle transfers the laser beam to the distal end where a lensed tip relays the beam from the fiber to the tissue. Fluorescence or reflected light from a resolution element is imaged back into the same fiber, propagates back to the proximal end, is collected and de-scanned by the confocal optical system, and is finally focused on the fiber aperture. This entire process occurs within the dwell time of the raster scan (2.5 microseconds in our design). During endoscopy, the 488 nm laser is focused by the distal tip at NA = 0.8 to a 0.4 micron diameter spot and scanned over an adjustable field (that can be zoomed from 10.8

to 108 microns) at a working distance of 80 microns. Our fiber optic spectrometer is based on a serial array of reflecting spectral elements, delay lines between these elements, and a single element detector. After excitation by a laser pulse, broadband fluorescence from a biological tissue sample propagates into the array via the confocal aperture, light of the first wavelength band reflects from the first element, and light of the Nth wavelength band reflects from the Nth element. Each wavelength is mapped into a specific time slot. Each delay line is equal to the length of the laser pulse. For the first time, we are reporting the implementation of 10 spectral bins - 5 coated fiber tips on the blue leg of the beam splitter, and another 5 coated tips on the red leg of the beam splitter. Each coated tip reflects light up to a transition wavelength. Each spectral bin is bounded by two of the transition wavelengths. Light from the blue array is detected before light from the red array. The key advantage of this design is speed. The 10 spectral bins are acquired during the dwell time of each pixel in the spatial scan.

All filters shift to smaller wavelengths according to $2ndcos\theta$ - where n is the effective index of the filter, d is the physical thickness, and θ is the angle of incidence from the normal. The blue shift shown in figure 1 at higher angles would cause unacceptable crosstalk in our fiber spectrometer. In multimode fiber, this crosstalk is avoided by using low injection angles at the fiber input, and high fiber bend radii. Crosstalk is also caused by the residual ripple at wavelengths above the transition wavelength. This crosstalk can be corrected in firmware. Each fiber tip connection to the adjoining tip leads to loss associated with core to clad coupling as light propagates through the filter. This loss is mediated by minimizing physical thickness of the filter.

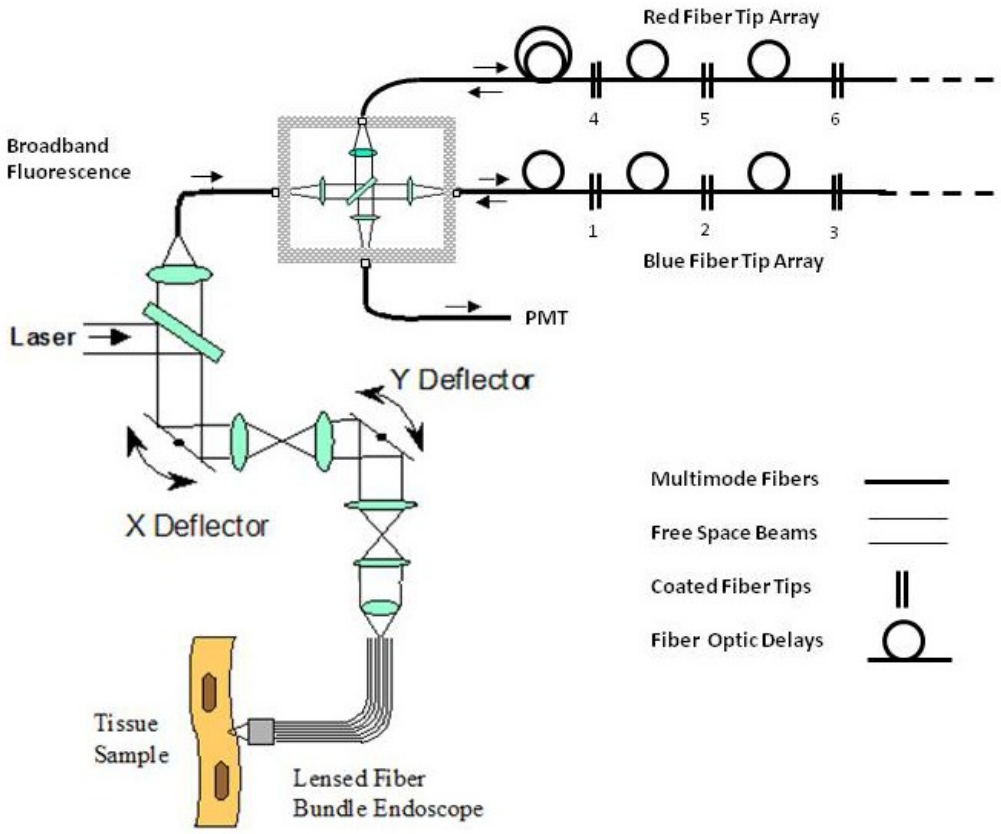

Figure 2. A multispectral confocal scanner using an array of coated fiber tips

3. FABRICATION

For this study, the high index layers were composed of zinc sulfide (index at 500nm equals 2.35), and the low index layers were composed of yttrium fluoride (index at 500nm equals 1.48). Both materials were deposited with an electron beam source under mid 10^{-5} torr vacuum levels. The electron beam source allows for a denser more robust filter than standard thermal sources with these materials. Coatings were deposited on the FC/PC connector tips of multimode fiber with NA = 0.21, and a core size of 62.5 micron (SMF-28). This fiber has a maximum external coupling angle of 12.1 degrees, and a maximum internal propagation angle of about 8 degrees. The deposition system is shown in figure 3. The deposition of each layer is controlled by monitoring the reflectance of the tip during growth. This is done by directing monochromatic light through a fiber feed-through into the vacuum system. The reflected light from the tip is collected with a beam splitter and sensed with a power meter. Cut points after each layer is complete are found by observing the oscillations shown in the figure. In-situ monitoring of the growing filter enables the system to adjust to the sticking coefficient of the fiber tips – often different than the sticking coefficient of glass substrates.

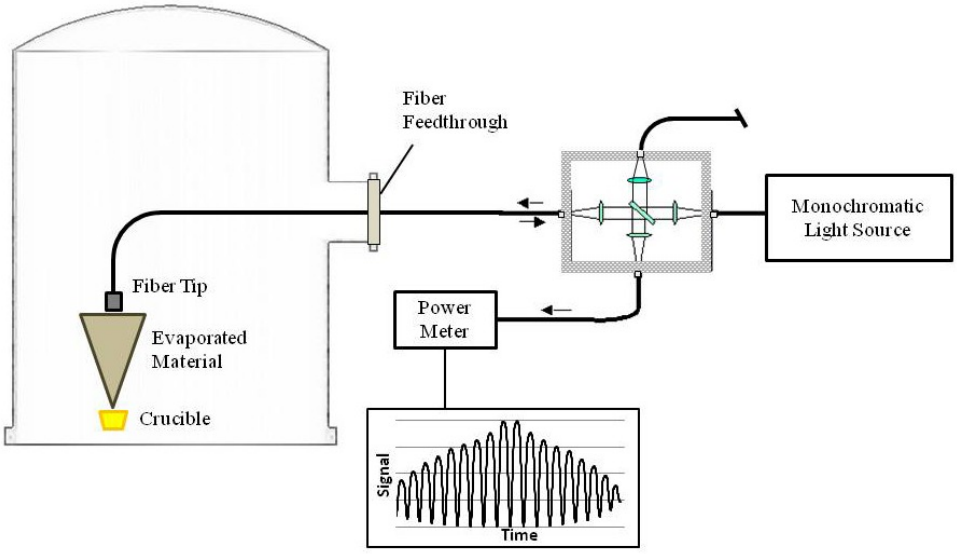

Figure 3. System for depositing and monitoring coated fiber tips

After growth, the fiber tips are either tested individually (see next section) or attached to other fiber tips to assemble a full array. In the arrays the coatings are immersed between the core glass of the sending and receiving fibers. Bend radii are controlled to keep the injected light in mostly lower order modes.

4. OPTICAL TESTING

After deposition, a modified version of the system in figure 2 is used to test the coated tips. The modifications are shown in figure 4. The sample and endoscope have been replaced by a bank of LEDs, a monochromator, and a multimode fiber. One leg of the beamsplitter is attached to the fiber tip array under test, and the other leg is attached to a known reference tip. During test set operation, the LEDs are excited with the short pulses normally used to excite the laser, the laser is off, and the scanning mirrors are fixed or limited to a small spatial sweep across the fiber core. Response curves are generated by selecting one LED at a time and stepping through wavelengths with the

monochromator (using 2nm steps). Reflected light form the known tip (S_{ref}) is acquired in the first time slot, while reflected light from an unknown tip (S_{tip}) is acquired in a subsequent time slot. Custom software digitizes S_{tip} / S_{ref} in real time. It should be noted that this hardware is not an interferometer because the two legs are not populated with light at the same time.

The solid curve in figure 1 shows that the measured performance of one discrete tip is similar to the model for a zero degree angle of incidence. At wavelengths below the transition, the data is about 10% lower than the model. This can be explained by losses in the fiber and connectors. The data matches the zero degree model rather well in the transition region. At wavelengths above the transition, the data can be a few % above the model. This performance is attributed to the deposition of a quality filter, the injection of low angles into the fiber array, and the avoidance of low fiber bend radii.

Figure 5 shows response curves for the integrated fiber tip arrays depicted in figure 2. Each tip is an edge filter reflecting wavelengths below a transition wavelength. Each band arrives at the detector in figure 2 during a different time slot. The bluest colors arrive first, and the redder colors arrive last. The curves for each tip have been scaled to have similar strength (by factors of 1 to 2) – much like one would handle the spectral roll off exhibited by diffraction gratings. The spectral resolution of this design ranges from 20 to 40 nm (each bin can be adjusted to a customized spectral width). The signals are completely independent of the state of polarization, and the entire spectrum of 10 bins is read out in about 2 microseconds with shot limited noise.

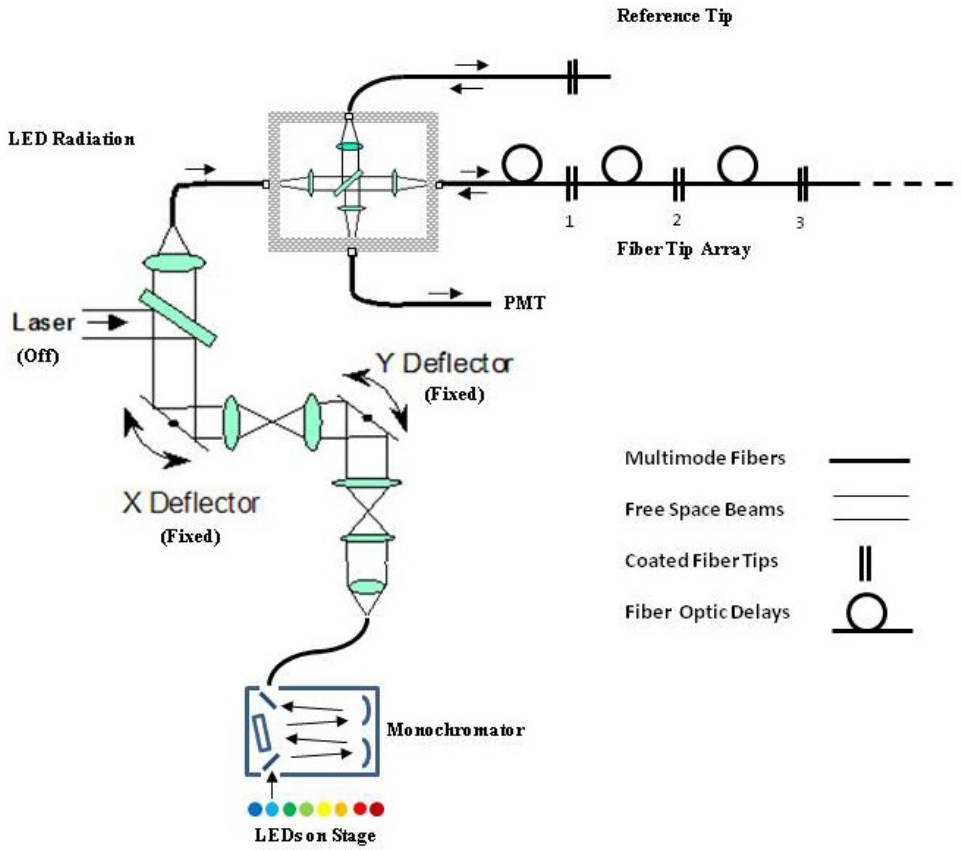

Figure 4. System for testing coated fiber tips

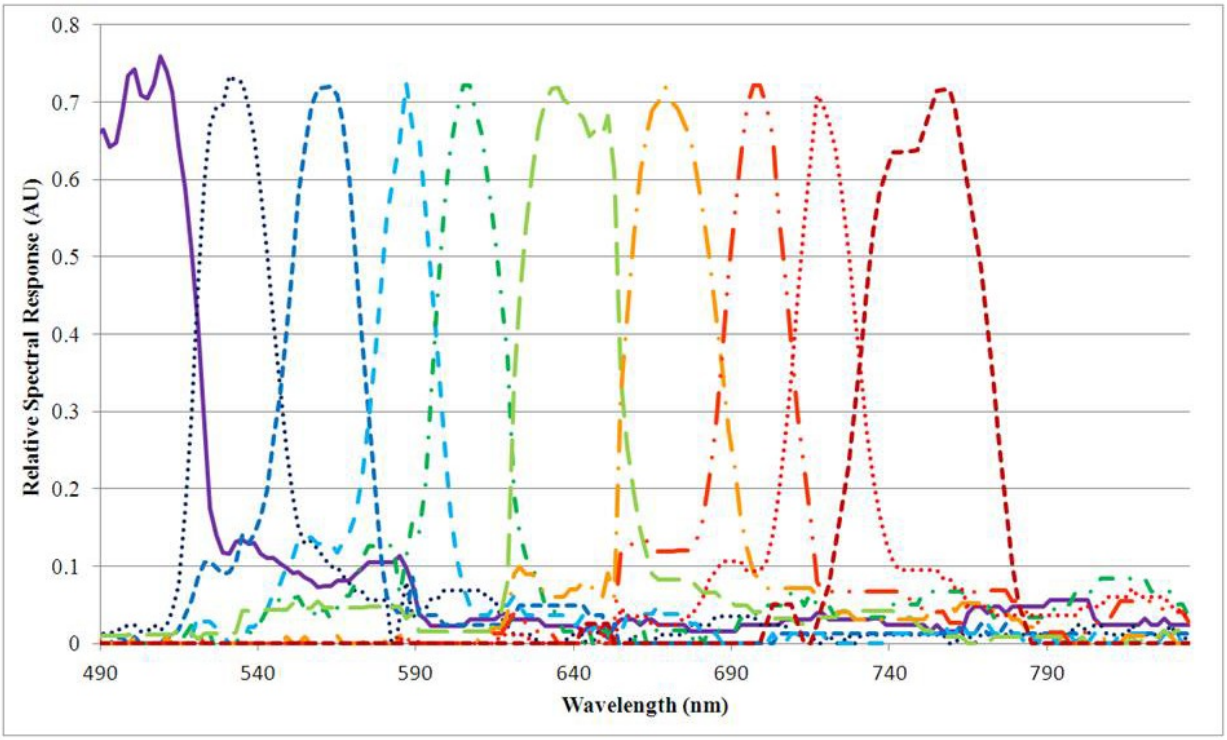

Figure 5. Spectral response of an array of ten coated fiber tips (in use, each spectral band is clocked out during a different time slot)

5. CONCLUSIONS

This paper has addressed the deposition and testing of filters deposited on connectorized fiber tips. Good agreement is observed between measured and modeled performance. The coated tips can be marketed as individual components or for assembly into serial arrays. The paper also addressed the use of these arrays in our multispectral confocal imaging system, where spectra can be read out in microseconds with the shot noise typical of PMTs and single photon arrays. Fast spectra are important for cancer imaging and cytometry (using pulsed laser excitation to synchronize with the arrays). Fast spectra using this technology can also be applied to remote sensing, but would require a fast broadband switch to synchronize with the arrays. The integration available with coated fiber tips leads to low cost designs that are also applicable to other applications including fiber lasers, interferometers, and Raman probes.

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