# Interference filters deposited on optical fiber tips

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Presented at SPIE Optifab, October 28, 2021

Citation:

J.B. Barton, S.K. Chanda, S.A. Locknar and G.E. Carver “Interference filters deposited on optical fiber tips”, Proc. SPIE 11889, Optifab 2021, 1188901 (28 October 2021); https://doi.org/10.1117/12.2601854

# Interference filters deposited on optical fiber tips

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## ABSTRACT

Many free space optical systems can be fiberized, enabling advantages in function, size and weight. Implementations include fiber-based lasers, interferometers, polarimeters, spectrometers, endoscopic probes, and pigtailed detectors. Interference filters can be integrated into a fiberized system by depositing the filters on fiber tips. Omega has deposited a variety of interference stacks on fiber tips. One can think of fiber tips as miniaturized substrates – the ultimate small part configuration. This article reviews optical fibers and fiber tips, coating fiber tips, testing the coated tips, as well as the performance and applications of the coated tips.

**Keywords:** Interference filters, optical fibers, coated fiber tips

## 1. OPTICAL FIBER

A brief review describing optical fiber is relevant – especially regarding the propagation angles supported within the fibers.[1] The mode-dependent angles of incidence at the coated tips must be considered when designing interference stacks. The spectral characteristics of all interference filters shift to smaller wavelengths with an increasing angle of incidence.[2]

Optical fibers are flexible waveguides composed of core glass surrounded by clad glass. Dopants are added to the glass to make the core have a slightly higher index than the clad such that total internal reflection occurs at the core/clad interface. In silica fibers, the core is typically doped with Germanium. Fluorine doped clad glass is used in applications that require a pure silica core to avoid laser induced fluorescence. Figure 1 shows how the numerical aperture (NA) of a fiber is related to the index of the core and clad. Guided waves propagate in the fiber if injected at an angle less than $\theta_0$. For examples based on a core index of 1.44, single mode (SM) fiber has an NA of about 0.1 ($\theta_0$ = 5.7 degrees, and $\theta_1$ = 3.9 degrees) while multi-mode (MM) fiber has an NA of about 0.22 ($\theta_0$ = 12.7 degrees, and $\theta_1$ = 8.7 degrees). In the near infrared, SM and MM fibers have core diameters of about 10 and 62 microns respectively. Optical power in SM fiber propagates as a Gaussian with minimal dispersion, and is therefore used in high bandwidth telecom applications. MM fibers support many modes that propagate over a distribution of angles. Each mode propagates at different group velocities - thus limiting the temporal bandwidth in larger core fibers. MM fibers do, however, exhibit a larger light gathering capability (or etendue) that is important in biomedical applications. The etendue of a fiber is the product of the core diameter and the NA. The V-number of a fiber is given as $V = (2\pi/ \lambda)$ d NA, where d is the core radius and $\lambda$ is the wavelength. A MM fiber can support up to $V^2/2$ modes. The V number is basically calculating the number of wavelengths that fit within the etendue. The so-called cutoff wavelength marks the boundary between MM and SM propagation in a fiber. Single mode propagation in the visible requires core diameters as small as 3 microns, while MM fibers can have core size in the 100s of microns. Fiber tips on many types of fiber have been coated at Omega.

The tips of optical fibers can be prepared in various ways. After being cut with a pair of scissors, the acrylic coating on the last few centimeters of a fiber is stripped by mechanical or chemical means. The exposed clad glass can then be cleaved to provide a pristine surface. These cleaved fiber tips can be coated, although fiber tips mounted within ferrules are more manageable in the deposition system. Ferrules are typically ceramic cylinders with axial holes that match the

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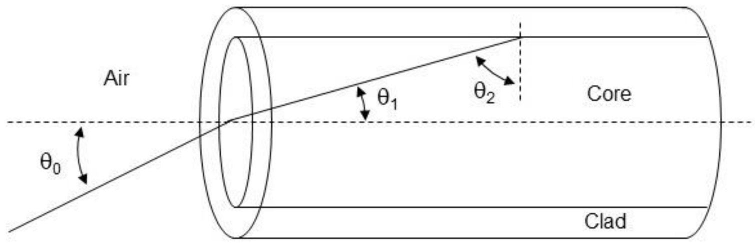
clad glass diameter. Fibers are inserted through the ferrule with a small length protruding past the end such that the tip of the fiber and ferrule can be polished. Omega coats this polished surface with interference filters. The ferrules are assembled into fiber connectors which can be connected to each other with fiber-to-fiber adapters. The FC connector uses a keyed structure that prevents the two fibers from rotating against each other. The FC connector comes in two versions – FC/PC and FC/APC. The PC tip is perpendicular to the fiber axis while the APC tip is tilted 8 degrees to avoid back reflections. Omega typically coats tips with either ferrules or fully assembled FC/PC connectors. Tips supported in other connector types as well as multiple cleaved fibers held in v-groove blocks can also be coated.

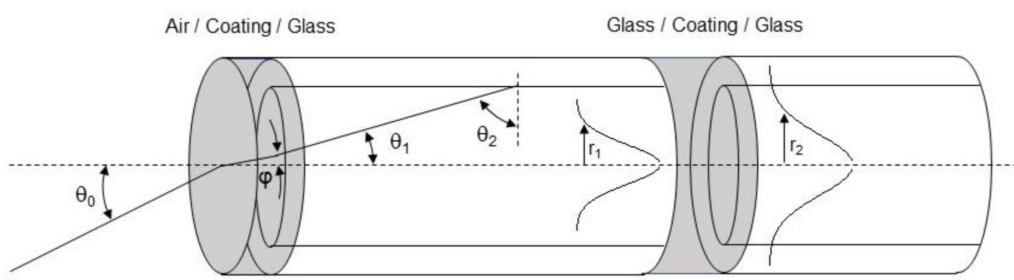



$$NA = \sin\theta_0 = n_{core}\sin\theta_1 = n_{core}\cos\theta_2 = n_{core}\,(1-\sin^2\theta_2)^{1/2}$$

$$= n_{core}\,(1-(n_{clad}/n_{core})^2)^{1/2} = (n_{core}^2 - n_{clad}^2)^{1/2}$$

Figure 1. Relationships between the numerical aperture (NA), refractive indices, and propagation angles in optical fiber

The shaded regions in figure 2 depict two filters applied to a fiber – one at the air glass interface and a second immersed within the fiber path. Applying Snell's Law from air into the filter, and then from the filter into the core, shows that the filter does not influence the NA of the fiber. On the other hand, the fiber influences the performance of the filter. The effective index of the interference filter is approximately equal to $(n_H * n_L)^{1/2}$, where $n_H$ and $n_L$ are the high and low indices within the interference stack.[2] As shown in figure 2, the internal angle φ can be calculated from the effective index and $\theta_o$. The passband of a filter shifts to shorter wavelengths according the value of cos φ. The following examples show to what extent this effect occurs for several filter designs. The coated connectorized tips can be attached to sources, optical paths, and detectors. In these cases, the coating design assumes glass/coating/air interfaces. The coated connectorized tips can also be connected to uncoated connectorized tips using fiber-to-fiber adapters. In these cases, the coating design assumes glass/coating/glass – ie an immersed coating. Figure 2 also shows how a Gaussian single mode can expand while propagating through an immersed coating (due to the absence of clad glass in the filter). This causes a minor loss for typical filter thicknesses.




$$NA = \sin\theta_0 = n_{filter}\sin\varphi = n_{core}\sin\theta_1 = n_{core}\cos\theta_2 = n_{core}\,(1-\sin^2\theta_2)^{1/2}$$

$$= n_{core}\,(1-(n_{clad}/n_{core})^2)^{1/2} = (n_{core}^2 - n_{clad}^2)^{1/2}$$

Figure 2. Coatings (shaded) applied to optical fiber – both exposed and immersed configurations

## 2. DEPOSITION ON OPTICAL FIBER TIPS

Fiber tips are coated using an electron-beam evaporation system for small lots, and a plasma assisted reactive magnetron sputtering (PARMS) system for larger volumes. Low to moderate temperature processes are appropriate for coating connectorized fiber tips.

The e-beam system currently deposits zinc sulfide (n at 500 nm = 2.35) and yttrium fluoride (n at 500 nm = 1.48). This method allows for reasonably robust semi-hard coatings. The deposition of each layer in the e-beam system 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.[3] 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 oscillations in the reflected signal. The incident light is provided by an Agilent tunable laser or a tunable light source from Energetiq. A spinner in the e-beam system supports up to ten fiber tips that spin around the fixed monitor fiber. Each ferrule is held by a clamp during the deposition process.

The PARMS machine deposits niobium oxide (n at 500 nm = 2.403) and silicon oxide (n at 500 nm = 1.479). This process deposits robust hard oxides. There are eleven pockets that usually hold flat substrates. Custom jigs fit in these pockets and hold the fiber tips during deposition. Omega operates multiple PARMS machines – the smaller system coats 66 fibers in one run while the larger system coats up to 264 fibers per run. An integrated optical monitoring system (OMS) in the PARMS system measures transmission through a monitor substrate. Offsets between the fiber tips and the monitor plate have been found to be nearly zero. This is accomplished by positioning the tips along the stripe that the OMS measures on the monitor plate. The uniformity from tip-to-tip in the near infrared is within 3 nm. The yield of fiber tip runs is nearly 100% - a pinhole must land on the core glass to make a coated tip unusable.

Optical fiber tips are cleaned by wiping with a tissue or a fiber cleaning tape. Inspection with a hand-held scope ensures that the surface is ready for deposition. During use, coated fiber tips are also wiped before being connected to an optical system or another fiber. This wiping operation must be done carefully with the semi-hard materials. The Helios hard oxides are capable of being wiped as aggressively as the uncoated tips.

## 3. TESTING COATED FIBER TIPS

Coated fiber tips are tested with both spectroscopy and microscopy. Three different light sources are used to measure the transmission or reflectance of the coated tips. Spectroscopy in the visible is done with 1 nm resolution using a tunable light source from Energetiq, or a bank of LEDs feeding a monochromator - both fiber coupled to a silicon-based power meter. Scans in the near infrared are done with 5 pm resolution using an external cavity laser (ECL) from Agilent coupled to an InGaAs-based power meter. A coil of fiber is placed between the sources and the tip under test to avoid clad light that would encounter the coatings at high angles of incidence. Deep optical density can be tested with either the Energetiq or the tunable laser. Quality control images in a microscope ensure that occasional dark spot defects are not located on the core glass.

## 4. OPTICAL PERFORMANCE OF COATED TIPS

A wide array of filters on fiber tips have been deposited and tested at Omega. The e-beam system is limited to a physical thickness on fiber tips of about 7 microns before coatings delaminate. The PARMS process has deposited robust coatings up to 30 microns thick on fiber tips. Measurements on fiber tips coated with partial reflectors, long pass, short pass, band pass, and antireflection coatings are presented in the following.

Figure 3 shows data for two partial reflectors – one targeted 70% and the other 10%. Each reflector was deposited in the e-beam system on single mode fiber and tested with the tunable laser. Even if these reflectors had been deposited on MM fiber, angle-induced blue shifts are clearly inconsequential over the wavelengths of interest.

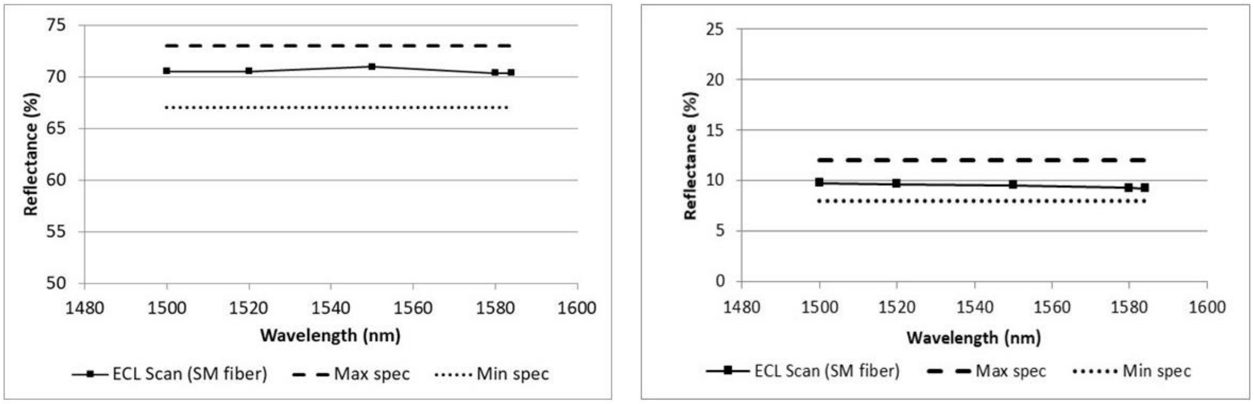



Figure 3. Partial Reflectors

Figure 4 shows transmission for two long pass filters in the short-wave infrared. Both long pass filters were deposited in the e-beam system on MM fiber. Data using the LED test set shown on the left of figure 4 trends from the 12.7 degree model at low transmission to the zero degree model at high transmission. Using the effective index of these coatings to compute the internal angle φ, we calculate that the edge should shift about 5 nm at 12.7 degrees. Figure 4 shows that the actual edge performance lies between the zero and 12.7 degree models. These small variations are expected based on which modes are populated during a given test.[4] The Energetiq data on the right side of figure 4 shows higher pass band transmission and less ripple, due to an improved execution of the manual e-beam system. The e-beam depositions generally provide a 20 nm wide transition, while the PARMS system can provide a 10 nm wide transition on fiber tips.

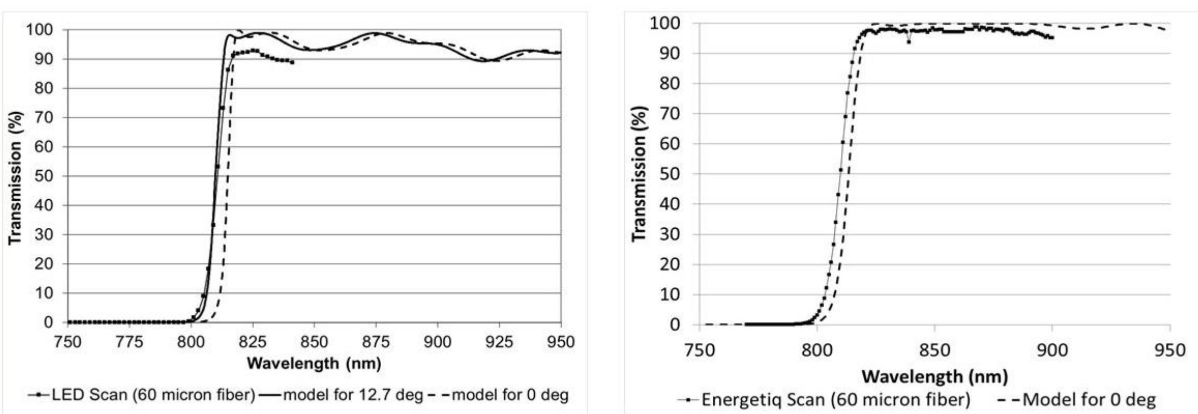



Figure 4. Long Pass Filters

Figure 5 shows transmission/reflection of short pass filters for applications in the short-wave infrared (left) and in the near infrared (right). Both coatings were deposited in the PARMS system. The spectral edge measured on SM fiber with the tunable laser perfectly matches the spectrophotometer scan on the flat glass monitor plate. The fiber exhibits higher pass band transmission relative to the monitor plate due to the absence of a back-side reflection. The plots on the left side of figure 5 are models, though also well matched by data. These hard oxide coatings exhibit an impressive damage threshold (~2E10 W/cm$^2$ near 800nm).

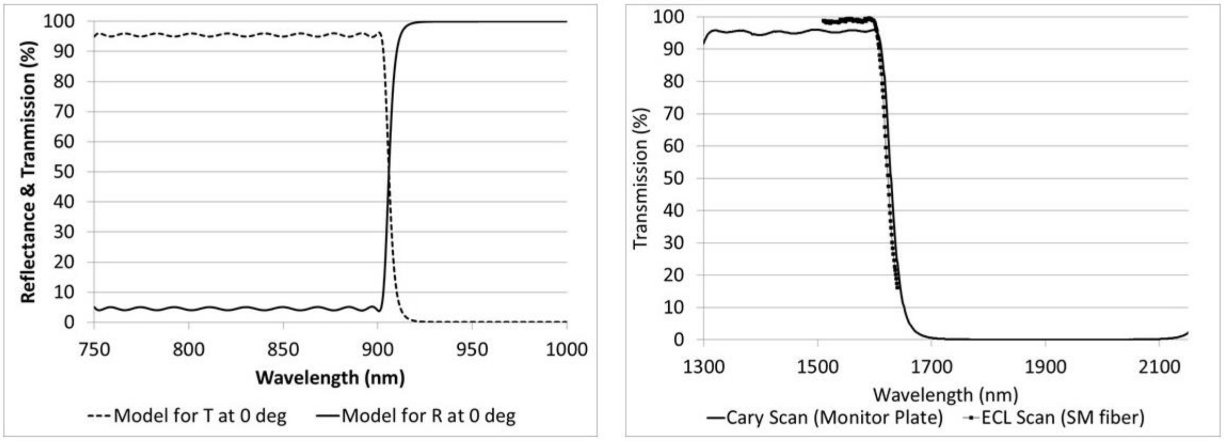



Figure 5. Short Pass Filters

Figure 6 shows the transmission for band pass filters near 787 nm and 1563 nm. The near infrared filter on the right side of the figure was deposited in the e-beam system on single mode fiber. This single cavity design has a spectral width at the half power points of 3 nm. The corresponding tunable laser data has a spectral width of about 5.5 nm. A higher and narrower spectrum would require improved thermal control in the manual e-beam system. The filter on the left side of the figure was deposited in the PARMS system on both SM and MM fiber. This is a 4-cavity design with a spectral width of 10 nm. The Energetiq scan on SM fiber shows an excellent match to the modeled band shape and width. The peak height was somewhat reduced by dark spot defects in the core region. The Energetiq scan on MM fiber shows the expected blue shift due to the angles of incidence supported in the MM fiber. The flat top design is also somewhat distorted, though the data still approximates the model. Again using the effective index of these coatings to compute the internal angle φ, we find that the peak wavelength should shift about 5.5 nm at 12.7 degrees. The date is consistent with a distribution of angles of incidence between zero and 12 degrees.

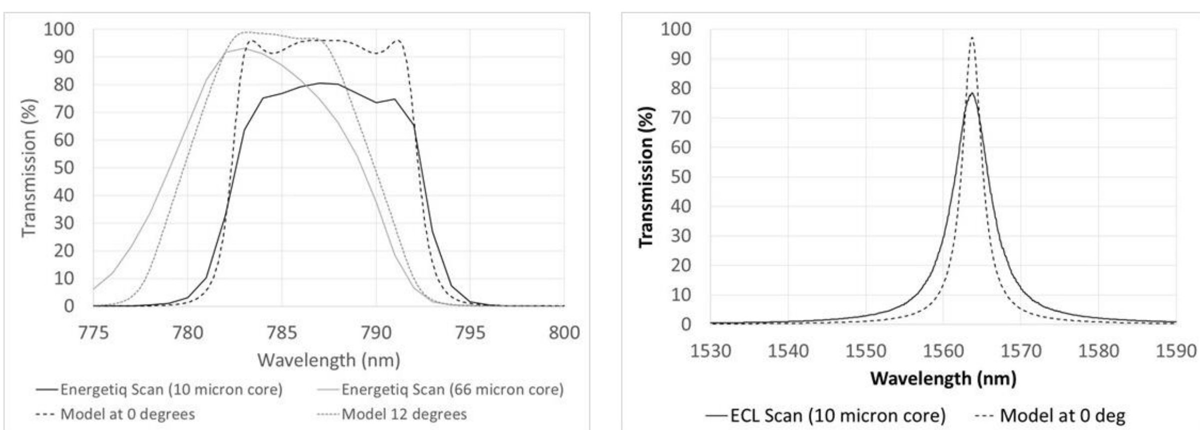



Figure 6. Band Pass Filters

Figure 7 shows the reflectance of antireflection (AR) coatings deposited for applications in the visible and near infrared bands. Omega is typically interested in spectrally complex coatings, though the broadband ARs in figure 7 have also been deposited on fiber tips. The left side of the figure shows good agreement between the Energetiq scan and the model across most of the visible. Reflectance of the monitor plate scan is high because of the uncoated back side of the substrate. The right side of the figure is a spectrophotometer scan of a witness plate covering the near infrared region (in this case the back side refection was removed mathematically). These coatings were deposited in the PARMS system.

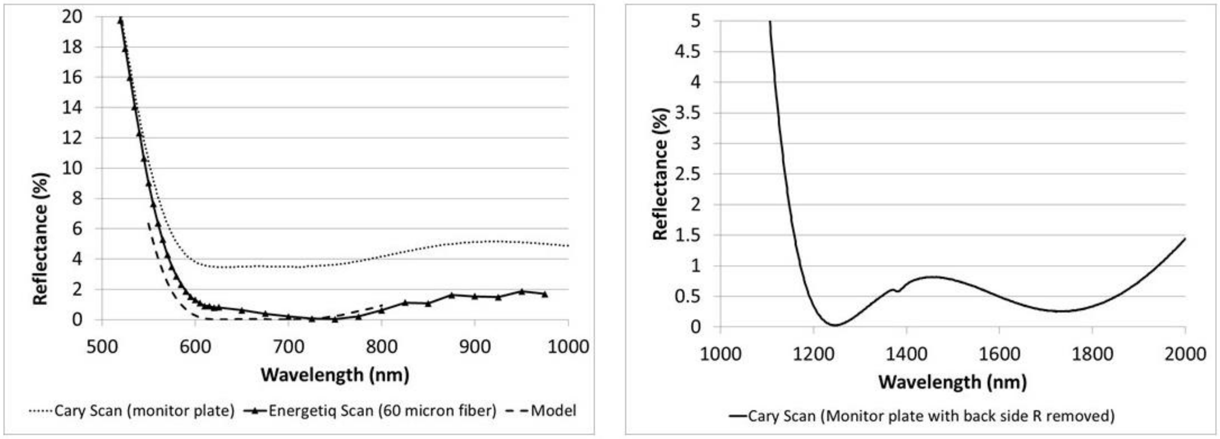



Figure 7. Antireflection Coatings

## 5. APPLICATIONS OF COATED FIBER TIPS

If a coated fiber tip is connected to an uncoated tip, it should be noted that the result is a two-terminal device. Incident light arrives on one fiber, some wavelengths propagate through to the second fiber, and other wavelengths reflect back into the first fiber. Other products that integrate multiple fibers, lenses, and free space filters can act as N-channel devices. In these cases, incident light arrives in one fiber while various color bands exit on other fibers. In yet other products, fused fiber and photonic lightguide circuits (PLCs) can distribute wavelength bands into multiple fibers. The following paragraph lists several cost-effective applications of coated fiber tips.

Omega has shipped coated tips to many customers who have integrated the tips into a variety of optical systems. The partial reflectors are used for fiber lasers and fiber-based interferometers. Short pass filters are used to protect pigtailed single photon detectors. Band pass and long pass filters are needed for endoscopic Raman probes. Long pass filters serve as short pass reflectors in fast spectroscopy. Finally, ARs are important for fiber-based photometry. Coated fiber tips can even be used within single photon generators for quantum computing.

## 6. CONCLUSIONS

Many if not most optical systems can be fiberized, and most filters can be deposited on fiber tips. Omega deposits complex dielectric stacks on fiber tips for a multitude of applications. Omega can handle small prototype lots in an e-beam system, and larger production lots in PARMS machines. The angle induced blue shift of certain coatings on MM fibers can be managed by taking fiber properties into account while designing the interference stacks.

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