Spectral Filters for Laser Communications

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Optical communication systems must perform reliably under strong background light interference. Since the transmitting lasers operate within a narrow spectral band, high signal-to-noise ratios can be achieved when narrowband spectral optical filters can be used to reject out-of-band light. This article develops a set of general requirements for such filters and provides an overview of suitable spectral filter technologies for optical communication systems.

I. Introduction

Optical communication systems will be required to function under diverse, sometimes hostile, channel-noise conditions. Various techniques and technologies will be employed to reject background light (optical noise), while, at the same time, providing maximum possible signal throughput efficiency. Spectral optical filters (SOFs) in this regard will play an important role in determining the system sensitivity.

An SOF is usually designed for a given center wavelength, λ_c, at which the filter provides maximum throughput efficiency, η. The throughput efficiency decreases as the incident wavelength moves away from λ_c. Wavelengths $\lambda_c \pm \Delta\lambda/2$, where the filter efficiency drops to 0.5 of its peak efficiency, defines the filter bandwidth, $\Delta\lambda$. These characteristics are critical to the performance of the SOF. The bandwidth of the filter determines how well it blocks out-of-band radiation from reaching the detector. The spectral bandwidth of the SOF should be as small as possible, especially if the detection process is limited by the background optical noise. Fortunately, spectral bandwidths of lasers, which are to be used as transmitters in optical communication systems, are extremely narrow. Narrowband SOFs tuned to the central frequency of the transmitter

laser can provide the necessary signal-to-noise ratio (SNR) under high-background conditions. However, due to possibly large, relative velocities between the receiver and the transmitter, Doppler shifts as large as 0.1 nm are possible. Hence, the narrowband SOFs must have the ability to tune their center frequency over this range.

Narrowband SOFs usually come with high insertion loss, which makes them unsuitable when noise background is low. For example, deep-space optical communication systems operating during the nighttime will be signal limited. Under such channel conditions, it will be important to obtain the highest possible signal throughput efficiencies, even at the expense of increasing the passband. As the bandwidth of the SOF is increased, the requirement on its tunability to counter Doppler shift becomes less critical.

Field of view (FOV) of an SOF is also an important parameter. For most filter systems the center wavelength shifts away from the design value with the angle of arrival of the signal beam at the filter. This results in a decrease in the filter throughput efficiency as the field angle increases. Other important properties of SOFs include clear aperture size and stability. Restrictions on both parameters arise from limitations on availability of suitable materials and manufacturability.

As stated earlier, optical noise can be very severe when the communication system has to operate within a few degrees of the sun (daytime), or relatively benign when operating during the nighttime. It is not expected that a single SOF system will be able to cover the whole range of possible channel noise conditions to provide optimal SNR for optical communication applications. Instead, several SOF systems, each optimized for a set of typical channel conditions will most likely have to be developed. The need for a narrowband SOF for use under high-background, optical-noise conditions, and a relatively broad bandwidth SOF with low insertion loss for use under dark background conditions has been identified.

To summarize, the fundamental requirements for these SOFs for optical communications will include the following:

(1) The narrowband SOFs for operation under intense background optical noise shall have

   (a) a passband of less than 0.05 nm

   (b) an overall transmission efficiency higher than 0.2

   (c) central wavelength tunability over 0.2 nm

   (d) central wavelength stability within 10 percent of the filter bandwidth

(2) The wideband SOFs for operation under low-background, optical-noise conditions shall have

   (a) a passband between 0.1 to 1 nm

   (b) a transmission efficiency of about 0.7

   (c) central wavelength tunability, as appropriate, to eliminate transmission loss due to Doppler shift

   (d) central wavelength stability within 10 percent of the filter bandwidth

(3) The field of view shall be as large as the design value for the receiver optics to minimize off-axis insertion loss and change in the center frequency.

(4) The clear aperture shall be as large as the design beam diameter for the optical communication instrument.

(5) The center wavelength of the SOFs shall match the center wavelength of the transmitter laser.

(6) Filter surfaces shall have negligible contribution to the system blur diameter.

Section II provides an overview of atomic resonance, birefringent, Fabry-Perot, Faraday, and other SOF technologies as well as information on manufacturability of such filters. In Section III, available SOF technologies and their relative merits for use with optical communication systems are discussed.

II. SOF Technologies

Several SOF technologies have been developed which may be suitable for optical communication systems. A discussion of such technologies and their capabilities is given below.

A. Atomic Resonance Filters

An atomic resonance filter (ARF) consists of an atomic vapor cell sandwiched between two conventional high-efficiency optical bandpass filters [1–6]. The input bandpass filter is centered at the input signal wavelength from the laser transmitter $\lambda_c(i)$. Light at this wavelength passes into the vapor cell and is absorbed. The atoms re-emit light at a shifted wavelength $\lambda_c(o)$. The output bandpass filter centered at $\lambda_c(o)$ allows the light to pass through, where it is then detected by a photodetector. If $\lambda_c(i)$ and $\lambda_c(o)$ differ from each other by several nanometers, relatively common SOFs can be used as input and output filters that have high throughput efficiencies and nonoverlapping passbands. Hence, the effective ARF bandwidth, which is essentially determined by the Doppler line width of the atomic absorption, is extremely narrow.

ARFs are based on atomic transitions and as such are insensitive to temperature fluctuations. Also, the vapor cells are insensitive to the angle of arrival of the signal light, i.e., ARFs possess a 2π-steradian FOV. The presence of input and output bandpass filters, however, will restrict the acceptance angle of the filter system to a few degrees.

ARFs operate at numerous discrete wavelengths. Table 1 lists some of the developed ARFs, with their operating wavelengths in the visible region [1].

The response time of an ARF is an important consideration, as it will determine the upper limit on the information rate. Typical rapid spontaneous emission times are ~30 nsec, which will allow an information throughput of about 30 MHz. However, it is possible to introduce a quenching gas, usually a noble gas, to decrease the response time, but at the expense of an increased passband. With this procedure, information rates in the gigahertz range are possible.

Filter conversion efficiency for the ARFs is defined as

$$\eta_c = \frac{N_o}{N_i} \qquad (1)$$

where N_o is the number of re-emitted photons at $\lambda_c(o)$ and N_i is the number of incident photons at $\lambda_c(i)$. It can be as high as 95 percent, as in the case of the Ca resonance filter at 432 nm [2]. For the Rb resonance filter operating at frequency-doubled Nd:YAG wavelength (532 nm), $\eta_c = 0.16$. However, with a vapor-cell design that traps 532-nm photons inside, η_c for the Rb filter can be increased to 0.28 [5]. For a complete Rb ARF filter system, which will include the input and output bandpass filters, the overall throughput efficiency, η, will drop to about 0.15.

The minimum ARF bandwidth is determined by the Doppler line width of the atomic absorption. Typically, this bandwidth is about 0.001 nm, which corresponds to about 1 GHz in the visible. However, optical communication systems may experience Doppler shifts as high as 50 GHz, due to relative motion between the receiver and the transmitter. This problem can be solved by introducing an inert buffer gas into the chamber. Collisions between the atomic vapors and the buffer gas can be used to broaden the passband of the filter beyond the Doppler shift. Also, the central absorbing wavelength changes with the buffer gas pressure, providing a mechanism for tuning the ARFs [3].

B. Birefringent Filters

Lyot-Ohman and Solc filters, two of the most commonly used birefringent filters, use an array of birefringent crystals and polarizers to select a narrow passband [7–11]. Typical materials employed for such filters are quartz and calcite.

A Lyot-Ohman filter consists of several crystal plates whose thicknesses vary geometrically, each twice as thick as its predecessor. The plates are separated by polarizing elements. Each birefringent crystal has a transmission spectrum given by

$$\tau = \cos^2[\pi \Delta n \ d/\lambda] \qquad (2)$$

where Δn is the birefringence of the element, d is the thickness of the crystal, and λ is the wavelength. The overall transmission spectrum of the filter is obtained by multiplying the transmission spectrum of each of the crystal

elements. The bandwidth of the Lyot-Ohman filter at full-width-half-maximum (FWHM) is

$$\Delta\lambda = 0.44\lambda_c^2/(2^{N-1}\Delta n \ d_0) \qquad (3)$$

and the free spectral range (FSR), i.e., the spectral distance between adjacent transmission maxima is approximately

$$FSR \simeq \lambda_c^2/(\Delta n \ d_0) \qquad (4)$$

where N is the number of crystal elements, d_0 is the thickness of the thinnest element, and λ_c is the central wavelength.

A Solc, or lossless, birefringent filter varies the angular orientation of the crystals rather than their thickness to achieve narrowband filtering. It consists of a series of birefringent plates of equal thickness between a single pair of polarizers. For an N-element filter, the orientation of the kth plate is given by

$$\phi_k = (2k-1)\rho \qquad (5)$$

with reference to the input polarizer axis where $\rho = 45/N$ deg. The transmission spectrum for this design is given by

$$\tau = \left[\frac{\sin N\beta}{\sin\beta}\cos\beta \ \tan\rho\right]^2 \qquad (6)$$

where $\cos\beta = \cos\rho \ \cos(\pi\Delta nd/\lambda)$.

More recent designs based on Solc filters are rugged, simpler to build, and have greater spectral versatility. These filters have the ability to place the passband at an arbitrary wavelength and can be tuned over a broad range. The transmission profile and the bandwidth can also be engineered with greater control. Rotating waveplate tuning has been used on a space-qualified, 0.005-nm bandwidth filter, which can be tuned to an accuracy of about 0.0005 nm [7].

C. Fabry-Perot Filters

The Fabry-Perot interferometer (FPI) consists of two parallel, flat, and transparent plates coated for high reflectivity and made of low-absorption materials[1] [11–17].

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[1] Product literature, Barr Associates.

The space between the two plates forms a cavity that is resonant at specific wavelengths determined by the optical thickness of the gap. The FPI transmits a narrow spectral band at each of a series of wavelengths λ, which are given by

$$m\lambda = 2nd \cos\phi \qquad (7)$$

where m is the order of interference, n is the refractive index of the medium in the gap, d is the thickness of the gap, and ϕ is the angle of incidence within the cavity. The transmission of an FPI is given by

$$\tau(\lambda, \phi) = \frac{T}{(1-R)^2}\left[1 + \frac{4R}{(1-R)^2}\sin^2\left(\frac{2\pi nd \cos\phi}{\lambda}\right)\right]^{-1} \qquad (8)$$

where T and R are the intensity transmission and reflection coefficients, respectively, of the coatings, which are assumed to be identical.

The total usable, angular field 2ϕ of an FPI is determined by the allowable shift $\delta\lambda$ in the central transmission wavelength across the field. It is given by

$$\phi = [2\delta\lambda/\lambda]^{1/2} \qquad (9)$$

measured in radians. If the allowable shift in center wavelength is $\delta\lambda = 0.025$ nm, and if $\lambda = 532$ nm, the resulting FOV of the FPI is found to be about 20 mrad.

The FPI can be tuned over a wide range by tilting it with respect to the incoming optical beam. For a tilt of magnitude $\delta\phi$, the shift in the central wavelength is $\delta\lambda = -(2nd/m)\sin\phi\,\delta\phi$.

Dielectric, thin film interference filters are the most abundant form of Fabry-Perot filters (FPFs). Multilayers of dielectric materials, such as cryolite and zinc sulfide, with differing refractive indices are deposited alternately on a substrate, usually glass. Thicknesses and the number of the alternating thin layers are engineered to allow peak transmission at the desired central wavelength λ_c and bandwidth $\Delta\lambda$. The passband range for interference filters is 0.2 to 50 nm. Interference filters with narrower bandwidths are possible by depositing increasingly larger numbers of dielectric layers. This makes such filters difficult to manufacture and quite fragile. Studies of narrowband interference filters have shown that the peak transmission wavelength drifts unpredictably to shorter wavelengths in time due to thermal and radiation shock [16]. Typical

transmission efficiency for a 1-nm bandwidth interference filter is about 0.7.

FPFs with a thick solid cavity, instead of interference filters, can be manufactured for passbands less than 0.1 nm. The reflecting layers are deposited on either side of a transparent substrate, usually made from a highly polished fused silica disk. Optical thickness of the substrate must be uniform to better-than-$\lambda/100$. Silica disks of thicknesses between 50 and 1000 μm, corresponding to a range of passbands between 0.1 and 0.005 nm, respectively, can be manufactured. The thicker disks are easier to manufacture. FPFs with bandwidth $\Delta\lambda = 0.03$ nm, diameter $D = 75$ mm, and transmission efficiency $\tau = 0.7$ have been reported [14]. However, an input passband filter is required to remove adjacent transmission channels, which reduces the overall system efficiency to about 0.5.

To obtain still narrower bandwidths, two solid etalons must be used in series. The second cavity is necessary to suppress the transmission channels adjacent to the desired λ_c, which are allowed to pass through the primary etalon. With this technique, it is possible to construct 0.005-nm filters with $\tau \simeq 0.2$, which employ two solid etalons and a conventional interference filter. By using a combination of tilt and temperature control, such a filter can be tuned over a range of 3 nm.

D. Faraday and Other Types of Filters

The Faraday anomalous dispersion optical filter (FADOF) has been discovered recently [18–19]. FADOFs are based entirely on the resonant Faraday effect. With the Faraday effect, the polarization of the incident light rotates as it passes through an active medium in the presence of a magnetic field. The relation between the angle α of polarization rotation and the applied magnetic field H is

$$\alpha = VHl \cos\psi \qquad (10)$$

where V is the Verdet constant for the active medium, l is the interaction length through the medium, and ψ is the angle between the direction of the magnetic field and the direction of propagation of the light beam.

The filter system consists of a vapor cell sandwiched between two crossed polarizers. When the applied magnetic field, the vapor density, and the length of the cell are properly adjusted, the polarization of only a narrow band of frequencies is rotated by 90 deg. This narrow band of frequencies is then transmitted by the output polarizer.

Unlike the ARF, the FADOF is an imaging filter, i.e., it does not change the spatial distribution of incident energy.

The bandwidth for the FADOF is limited by the Doppler line width of the atomic vapor, which is about 0.001 nm in the visible. The response time is also limited essentially by the Fourier transform of the Doppler bandwidth, which is about 1 nsec for the visible region. The FADOF, like the ARF, has a wide FOV.

In a laboratory setup the peak throughput efficiency of the FADOF system, which consists of an Rb vapor cell and two crossed polarizers tuned to a center frequency $\lambda_c = 780$ nm, has been shown to be about 0.63. Theoretical models predict throughput efficiencies higher than 0.9. The ability to track Doppler shifts in the signal due to relative motion between the transmitter and the receiver is being investigated.

A number of unconventional concepts in optical spectral filters using photorefractive, acousto-optic, and electro-optic effects are currently under investigation. However, the technology for such filters has been unable to produce narrowband SOFs with reasonable efficiency or is simply not yet mature enough for use with the optical communication systems.

III. Discussion

For comparison and ready reference, various filter capabilities have been summarized in Table 2. It is assumed that the center frequency for the compared filters is 532 nm, except for the FADOF, for which the results for a 780-nm filter are listed. The bandwidth, efficiency, and clear aperture columns in the table show typical values. The filter efficiencies shown here are typical of a complete SOF system. For example, the efficiency of a single cavity FPF can be as high as 0.7, but for a complete system, which must include a bandpass filter to reject adjacent transmission bands, the transmission efficiency drops to about 0.5. The FOV is calculated for a shift in the center frequency equal to half the listed bandwidth for each of the filters at 532 nm.

Typical dielectric interference filters can provide 0.2-nm bandwidths with throughput efficiency $\eta \simeq 0.7$. To obtain bandwidths $\Delta\lambda \leq 0.1$ nm, solid cavity FPFs are used. Such filters must be placed in a temperature-controlled environment. This temperature-controlled environment can,

however, be used to tune the central wavelength of the passband at a typical rate of 0.02 nm/deg C in the visible range. With active temperature control, FPFs with a single cavity can provide bandpass as small as 0.05 nm in the visible, with $\eta \simeq 0.5$. The peak throughput efficiency for double cavity FPFs, however, falls to about 0.2 for bandwidths as small as 0.005 nm. Another important limitation on the double cavity FPFs relates to the FOV, which is on the order of a few mrad. Currently 0.05-, 0.2-, and 1-nm bandpass filters can be routinely fabricated up to dimensions of 3, 5, and 15 cm, respectively [17]. Larger sizes are available by custom processing.

Birefringent filters provide an attractive alternative when narrow bandpass filters are required. Such filters, with bandpasses between 0.04 to 0.3 nm, are possible with 0.25-transmission efficiency. Aperture sizes of 7 cm can be fabricated.

The ARFs provide extremely narrow passbands with reasonable efficiencies, and, unlike the FPFs and the birefringent filters, they do not have a strong restriction on the FOV. The ARFs provide greatly improved performance, but only for background-limited detection. Hence, this is the only case that warrants the additional complexity associated with ARF use, as compared with conventional optical filters.

The newly discovered FADOF has wide FOV and narrow bandwidth comparable to the ARF. The FADOF throughput efficiency is expected to be much higher. Also, the FADOF can be used in applications where the preservation of the incident image field is necessary.

Figure 1 graphically shows the relationship between the bandwidth, $\Delta\lambda$, and the overall throughput efficiency, η, for the various filters discussed above. Figure 2 shows the relationship between $\Delta\lambda$ and the filter system FOV. In either of the two figures, a good candidate SOF for optical communications will lie in the upper left quadrant. It seems that the FADOF can potentially be an important addition to the SOF technologies for optical communications. However, more work needs to be done to resolve questions on its tunability and to develop a viable and robust filter. The double cavity FPFs may not be able to provide the necessary FOV, and may have to be dropped in favor of the ARFs when the signal is limited by the background noise. Cheaper single cavity FPFs, birefringent filters, or interference filters may become useful when wider bandwidths can be tolerated or are desired.

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Table 1. Operating wavelengths for developed ARFs

Atom	$\lambda_c(i)$, nm	$\lambda_c(o)$, nm	Pumping Source
Ca	465, 459	452, 894	Passive
Rb	Over 20 between 487–776 (including doubled Nd:YAG)	420	Diode laser
Mg	516, 517, 518	383	Optical
Tl	535 (doubled Nd:BEL)	378	Photochemical, thermal

Table 2. Filter characteristics comparison chart

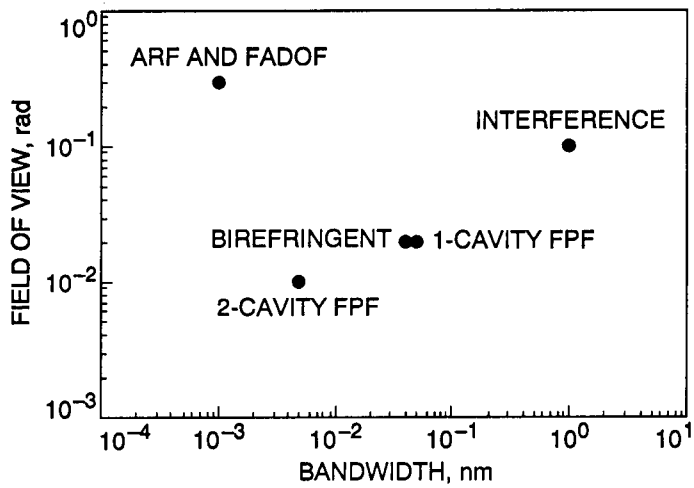| Filter	Bandwidth, nm	Efficiency	FOV, rad	Clear Aperture, cm	Tunability	Stability	Complexity	Coverage
Atomic resonance filter	0.001	0.15	0.3	Large	Low	High	High	UV to visible
Birefringent filter	0.04	0.25	0.02	7	High	High	Moderate	UV to near IR
Fabry-Perot filters:								
Interference	1	0.7	0.1	15	High	Low	Low	UV to IR
Single cavity	0.05	0.5	0.02	5	High	High	Moderate	UV to IR
Double cavity	0.005	0.25	0.01	3	High	High	Moderate	UV to IR
Faraday anomalous dispersion optical filter	0.001	0.63	0.3	Large			Moderate	UV to IR
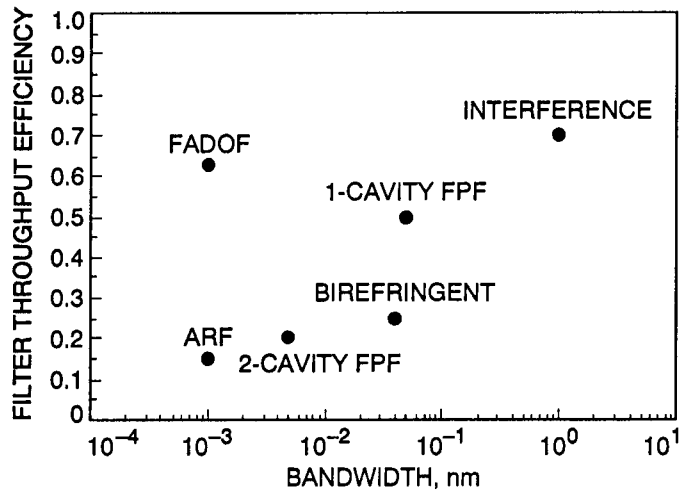
Fig. 1. SOF throughput efficiency versus bandwidth.

Fig. 2. SOF FOV versus bandwidth.