SPECTRAL FILTERS FOR LASER RANGING

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ABSTRACT

The available means of enhancing laser ranging system performance by means of spectral filters are reviewed. Multi-layer dielectric, Fabry -Perot, and Dispersive filters are described, with emphasis on the operational deficiencies and benefits of each filter type. Some projections for the future in spectral filtering for fully optimised system performance are given.

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1. Introduction

The need for enhancement of signal-to-noise ratio (SNR) in laser ranging systems by means of spectral filtering is continually increasing. For SLR systems the most severe requirements arise for mobile systems which have generally smaller lasers and less well defined coordinates than fixed stations. The combination of poor a priori station coordinates and prediction uncertainties mean that temporal and spatial filtering of the signal is limited, and only spectral filtering can be intensified to enhance SNR.

For LLR systems, it is usual to operate temporal, spatial, and spectral filtering at the design limits of the system, since signal levels are extremely low and noise can be very high (e.g. full moon or daylight ranging).

For laser ranging systems there are two principal parameters which characterise the system performance, signal and SNR. The goal is generally to maximise both, and various measures are taken to accomplish this in terms of varying or modifying system parameters. For example, doubling the laser power doubles signal and SNR, whilst doubling telescope aperture increases signal fourfold whilst not affecting SNR at all.

One of the most cost-effective ways in which most ranging systems can be upgraded is by improving the performance of the spectral filter. Halving the passband of the system spectral filter will double SNR. Doubling the filter throughput efficiency in the passband will double signal. Thus, for example, if an operational system could replace a 1.2A filter of 20% efficiency with a 0.6A filter with 40% efficiency, this would result in a doubling of signal and SNR - the same affect as doubling the laser power, at possibly far less expense.

Considerable emphasis on filter design and selection is also required in the design of minimal, portable, or eye-safe SLR systems.

This paper reviews the filter technology that is available to todays system designers, with the emphasis on operational characteristics. Three basic filter types are reviewed:

(a) Multi-Layer Dielectric Filters (MLDF)

(b) Fabery Perot Filters (FPF)

(c) Dispersion Filters (DF)

2. Multi Layer Dielectric Filters (MLDF)

The principles of operation of MLD filters are well documented in the literature, and widely known. The term MLDF is usually used in the context of laser ranging systems to refer to a composite device consisting of an all-dielectric filter, an induced transmission filter, and a broadband (glass) blocking filter.

The particularly useful features of MLDFs are:

1. Compactness
2. Ruggedness
3. Easy to temperature control or temperature tune
4. Relatively insensitive to incidence angle
5. Single passband only

These features represent why the MLDF is the basic and universal filter for laser ranging systems. It is only in the area of filter efficiency, or transmission, where high performance requirements are difficult to meet with MLDFs. Typical transmission efficiencies for fully blocked filters range from 60% at 10A bandwidth to 20% at 1A. Other filter types become superior in transmission for filter bandwidths below about 3A.

For filter bandwidths in excess of 3A, efficiencies of 50% (and higher) can be obtained for MLDFs. This value of throughput, together with the advantages listed above, make them the natural first choice for most laser ranging systems.

3. Fabery Perot Filters

MLDFs evolved several decades ago from classical Fabery perot filters (FPF). The family similarities remain in that both use interferometric principles to enhance or retard transmission. FPFs, however, use two mirrors separated by a distance which is very large compared to the wavelength of light, and for some applications this original configuration can be utilised to better effect than the MLDF.

In particular, high transmission efficiencies coupled with very narrow bandwidths may be realised. For example, a blocked FPF with 0.5A bandwidth may have 40-60% transmission at line centre - approximately double that realisable with an equivalent bandwidth MLDF. At first sight this looks extremely attractive, but there are many factors weighing against the operational application of FPFs.

The principal difficulties with FPFs arise in the following areas:

(a) Free Spectral Range (FSR) and blocking

(b) Bandwidth control

(c) Angular sensitivity

(d) Vibration sensitivity

(e) Temperature sensitivity

(f) Field-of-view (FOV) problems

(g) Alignment/Servo is highly specified

The Free Spectral Range (FSR) is the distance from one peak of transmission to another in the 'comb' response of the FPF. It is given by

$$FSR = \lambda^2/2d$$

where λ = centre (design) wavelength

d = plate separation

The finesse (F) of the filter is made up of a number of terms, but in practice is usually given by

$$F = \pi R^{\frac{1}{2}}/(1-R)$$

where R = reflectivity of FP mirrors

Bandwidth (BW) is given by

$$BW = FSR/F$$

If (typically) λ = 532 nm

d = 0.1 mm

F = 28

then FSR = 14A

BW = 0.5A

This represents a typical FPF design.

Now the overall efficiency of the FPF itself may be as high as 85% if the device is very precisely manufactured and aligned. However, because the passband recurs at a frequency given by the FSR, a blocking filter must be used to eliminate all but the desired passband. The blocking filter passband must be less than the FSR to avoid passing more than one passband. In the above example, a 10A MLD filter would be used, yielding an overall efficiency of around 50%.

FPFs are extremely sensitive to angle detuning, because the interferometric operation depends upon the path length travelled between mirrors to be an integral number of half wavelengths. It is simple to establish the angle sensitivity as

$$\Delta\lambda = \lambda_c \left(\frac{1}{\cos\theta} - 1\right)$$

or

$$\theta = \cos^{-1} (\lambda_c/(\lambda_c + \Delta\lambda))$$

for $\lambda = 5320$ A

$\Delta\lambda = 0.1$ A

then $\theta = 1264$ arc sec.

If the filter is working at a X60 demagnification from the receiving telescope, then the centre wavelength of the filter will move 0.1A over a 21 arc second field of view. More significantly, the filter must be held stable to 21 arc minutes (1264 secs) in its holder if the centre frequency is not to move by more than 0.1A.

It is important to note also that spatial filtering must complement the FPF, since the filter only 'works' at normal incidence, and the passband simply moves (spectrally) with angle of incidence. That is, the system FOV is dictated by the FPF design.

Temperature effects can be the limiting factor in FPF implementation. Even INVAR stabilised mounts can 'walk' a filter line centre by up to 3A per °C. For a 0.5A filter, 0.5°C temperature control is totally unsatisfactory.

A recent development has been the active control, using PZT or similar drive, of the parallelism and spacing of the FP mirrors. Using a CW laser injected off-axis and directed to a detector, the FP tilt and spacing can be servo controlled for optimum performance. The off-axis alignment laser can be at any wavelength, but is often at 6328A as little power is required. A dither technique is used to lock the FPF to line centre of this laser, and the on-axis passband tuned to the desired wavelength by tuning the incidence angle of the alignment laser. This technique has been very successful in overcoming mount creep, temperature drift, and even some vibration-induced detuning of the FPF in tests at the Orroral Observatory. However, the hardware is complex and sensitive, and major efficiency improvements over MLDFs must be demonstrated before the major task of integrating FPFs should be undertaken.

The Orroral Observatory is extending its examination of FPF characteristics to determine the realisable peak transmission efficiency, the long term stability, and the (light) noise immunity of FPF servo systems.

4. Dispersive Filters

Both refraction and diffraction can be used as the dispersive mechanism for dispersive filters. Refractive-Dispersive Filters (RDFs) and Diffractive-Dispersive Filters (DDFs) are both common in a wide range of optical applications. It is only recently [1] that either has been used for laser ranging.

The principal of operation of these devices is extremely simple. The spectral dispersion of the incident radiation allows spatial isolation of narrow wavebands of interest by means of spatial filtering (pinholes, slits).

The significant features of DFs in general can be summarised as:

(a) temperature stable

(b) vibration/mechanical noise sensitive

(c) complex design and optical fabrication

(d) relatively high efficiencies possible

(e) widely and easily tuneable

(f) efficiency not bandwidth dependent

(g) bandwidth also tuneable

(h) bandwidth and field of view not independently adjustable

(i) precision alignment necessary

Apart from these general characteristics, each type of DF has specific advantages and disadvantages. DDFs have an unfortunate characteristic which causes temporal dispersion of the processed optical signal. Precision correction for this effect, due to the non-normal incidence of the input beam on the grating, is extremely difficult. Thus an additional ranging error is introduced. Further, the dispersive mechanism is not more efficient than 50-60%. Finally the coupling of bandwidth and FOV by the exit slit (spatial filter) results in impractically small FOV for very narrow bandwidths. A typical DDF [1] will give 3.5A per 60 arc sec FOV. Thus a 0.5A exit slit would give a maximum FOV of 9 arc seconds. Increasing the FOV is not possible without expanding the BW also, despite the fact that this is detrimental to system performance. The example given will give a BW of 2A for a FOV of 35 arc seconds and an efficiency of 50%, a performance level around which an excellent SLR may be built.

RDF characteristics do not include temporal dispersion of the signal, and efficiencies near 90% are feasible. The major limitation with RDF application is the practical limit to the size of dispersive prisms which can be constructed. This limits the degree of dispersion attainable, and filters for (typical) ranging configurations may be limited to 3A (min) by this. However, it is unlikely that an RDF of less than 3A would be of general use, since the FOV for smaller bandwidths becomes unreasonably small.

5. Future Developments

Further development is likely to see incremental improvements in MLDF efficiency at all bandwidths.

The use of FPF technology should move gradually into the operational sector from the research environment.

A most promising long term development is the combination of FPF and DDF to form 0.5A filters with 75% throughput in the centre of the passband. This proposed design would use the DDF in its optimum role - as a high efficiency wide band filter. Thus the DDF would not limit the system FOV. If a DDF was used as (say) a 10A block for a 0.5A FPF with 14A free spectral range, an efficiency of 90% is possible, with a working FOV of an arc minute. This FOV can then be controlled independently of the spectral filtering process using a conventional lens/pinhole combination. This is not really necessary, since in the DDF/FPF combination, the DDF can be used as the spatial filter as its transmission efficiency will not vary as its FOV and bandwidth are tuned. Clearly a FOV corresponding to a DDF bandwidth greater than 14A cannot be selected, since the DDF is then not effectively blocking the FPF. Similarly, a FOV corresponding to a DDF bandwidth of less than 0.5A cannot be selected without reducing the effective bandwidth of the DDF/FPF combination. This lower limit of filter bandwidth is most likely to be fixed by the power spectrum of the laser. For a 100 ps laser, a filter of around 0.6A is needed to transmit the power spectrum. If a 0.6A FWHM filter is used, a large proportion of the signal from a 100 ps laser will be transmitted at an efficiency below the peak transmission of the filter.

For the example given above, if a FPF efficiency of 85% can be achieved routinely, then the spectral filter will operate at 75% efficiency for 0.5A bandwidth over a wide range of FOV. This is four times better than MLDF performance, and almost 1.5 times as good (efficient) as a MLDF blocked FPF.

Large systems, and particularly LLR systems will gain 300% to 50% improvements in data production over current capabilities at 0.5A.