Wavelength budgeting for optical filters

Abstract:

Considerations when specifying transition pass bands, blocking bands, and transition widths include filter manufacturing tolerances, thermal tolerances and source/detector variations among others. These factors must be taken into account properly and completely in order to achieve the spectral performance required for an application.

Introduction:

We are all familiar with budgeting in our daily lives – budgeting our time or finances between different activities that are priorities (family, work, self-care, food, shelter, clothing, heath, etc) or optional activities (entertainment, hobbies, travel, etc). We are always making trade-offs between “need to have” and “nice to have” options and sometimes even balancing allocation of time or money among the “need to have” items.

The same budgeting exercise is necessary when it comes to specifying optical filters. There are always trade-offs to be made between specific optical performance specs and costs and the use conditions that lead to these specs.

One of, if not, the primary user influenced considerations in most wavelength selective (band pass (BPF) or edge pass (LPF or SPF and notch) optical filters is the allowed spectral transition zone between high transmission wavelengths and high blocking (or reflecting) spectral bands as defined by the requirements of the device in question. Specifying this transition zone, or “dead band” as we like to call it, is a key driver in complexity and cost of most optical filters as it directly constrains the required steepness of the filter. In different applications this might be called “band spacing” or “channel spacing” or “isolation bandwidth” (among other terms). This spectral separation defines the total budget that we have available to “spend” on the influences due to the application and those due to realities associated with filter manufacture.

There are a few key application uses and filter manufacturing parameters that influence the spectral width of dead-band and so we’ll discuss here these parameters and how they consume the wavelength budget of optical filters.

Application influences on wavelength budget:

There are three primary application related “consumers” of the available wavelength budget; these are parameters that are under control of the application designer (as filter designers we can only indicate the impact of these parameters and have little opportunity to reduce or optimize for these effects).

1) Operating temperature range:

    All optical thin film filters will experience a shift in the spectral performance as a function of the operating temperature. Most filters will shift to longer wavelengths with increasing temperature although some mid-wave infrared (MWIR) filters use materials that shift to shorter wavelength with increasing temperature. The direction of the shift with temperature is, however, not important as what matters is the total temperature range over which the filter needs to operate (a design can be targeted for operation at any nominal temperature although the shift does need to be factored into the design and characterization (especially if the filter operates at a different temperature than the test conditions)).

    The thermally influenced wavelength drift (ΔWL_{Temp}) of a filter is typically specified in terms of the temperature coefficient (T_c in units of pm/C) with typical values ranging between 1-2pm/C up to 10-20pm/C depending on the substrates and coating materials multiplied by the temperature range of operation.

    $$\Delta WL_{Temp} = T_c \text{ x } (\text{Max Temp} - \text{Min temp})$$

    For example, a filter with a 10pm/C thermal drift that needs to work from -20C to 80C will experience 1nm of thermal drift from the thermal extremes (10pm/C x 100 C = 1000pm (or 1nm)). This value will need to be subtracted from the budget defined by the band spacing requirements.

2) Operating angle of incidence and angle range:

    Multilayer thin film optical filters will experience a “blue shift” to shorter wavelengths with increasing angle of incidence. Similar to temperature range above, the nominal angle at which a filter needs to operate can be accounted for “by design” and needs to be factored into characterization; what matters with respect to wavelength budget is the range of angles over which the filter needs to meet all optical specifications. This range can be due to uncertainty (typically referred to as the angular tolerance) in the nominal angle of incidence (AOI) and/or a variation in the angle on the filter caused by a focused or divergent (ie not collimated) incident beam (typically specified as the cone half-angle (CHA)). However, this shift with angle is non-linear so a filter with a nominal AOI of 0 deg and a total angular contribution of +/- 5 deg will experience a much smaller spectral shift than a filter with a nominal AOI of 45 deg and a total angular contribution of +/-5 deg. Where possible operating at a smaller nominal AOI is recommended to minimize the impact on budget.

The actual value of spectral shift is highly design dependent so it is not possible to provide a typical scale of shift with AOI. Designs can be adjusted somewhat to minimize spectral shift or alternate material sets can be chosen but there is limited design freedom to adjust this parameter.

3) Polarization

The polarization states of the light used in an application can also impact the wavelength budget. Once again the actual polarization state used (s or p polarization) is not important but rather the need for the filter to work for a single polarization state, over both polarization states, often termed random polarization (ie must be fully functional for s and p) or average polarization (ie must work when the average of s and p polarization is considered (this is often used in definitions but is not a valid description of actual use conditions)). A filter specified for use at a single polarization (or for use at or near 0 deg where s and p align) will have no contribution to the wavelength budget from polarization. In contrast a filter designed to work at a large AOI or over a large angle range for both polarizations will have to include a large wavelength budget contribution to account for the differences in spectral shape for each polarization at different AOI values.

If uncertain it is best to assume the filter needs to work for random polarization; any other case requires explicit control of the polarization of the incident beam (typically only seen in laser clean-up filters).

4) Source/Laser wavelength variation

The source wavelength of incident light used in any optical system will vary; the variation may be relatively small such that it can be ignored (e.g. sub GHz variations between HeNe lasers), or it can be relatively large (e.g. as much as +/-0.1% for some solid state lasers). In some cases each individual laser is stable, but there is a device to device variation such that there is still an uncertainty in the wavelength that the filter will see in use. The result is that the dead-band in a system requiring filtering of two different nominal wavelengths needs to be adjusted to account for this uncertainty, thus reducing the total available wavelength budget.

Filter manufacturing influences on wavelength budget:

Beyond the requirements of the filter in application, there are several aspects of the actual manufacture of filters that also need to be considered in the wavelength budget.

1) Filter design

Virtually any filter shape can be designed but in practice manufacturing variations of “real-world” production are critical. Filters must be designed with consideration given to factors such as the coating materials to be used (what is available and reliable) and minimization of complexity/thickness. Increased thickness of coatings negatively influences cost along with other parameters such as wavefront error and surface quality. In practice there is a maximum value to the achievable design edge steepness so the slope of this edge always takes up some of the total wavelength budget.

2) Wavelength targeting

Once designed the filter needs to be manufactured. In this process it is extremely unlikely that the edges of the spectral curve will line up exactly with that of the design. This wavelength targeting offset needs to be estimated at time of quotation and budgeted for spectrally. The wavelength targeting budget can be minimized somewhat if the filter can be actively angle tuned in application (ie tilt tuned to match the ideal spectral edge position) or by reducing the assumed run success rate, assuming that with multiple attempts eventually the edges will line up with design – this is a very costly approach to reducing the wavelength targeting budget.

3) Coating non-uniformity

Especially for larger parts (anything larger than a few mm’s) spatial variations in spectral performance due to coating non-uniformities must also be factored into the wavelength budget. Similar to wavelength targeting below, non-uniformity is manifested as an offset in the spectral edge position as compared to the design – the key difference is that this offset can be different at different positions on the part to the geometry of the coating approach used. The total expected uniformity variation (ie variation in edge wavelength) must be subtracted from the total allowed wavelength budget. This may be reduced by coater configuration but can often require set-up runs and again is a relatively expensive approach that may quickly run into diminishing returns especially for larger parts (eg 50mm). Also the non-uniformity is highly design dependent so what is a “large part” from a uniformity perspective will depend on the spectral performance that is being targeted.

Budget Calculations – a hypothetical example

The following example illustrates the various consumers of wavelength budget discussed above and how this can result in a filter that is not possible to make as specified.

NOTE: the values below are not intended to be representative of a real system, in particular the manufacturing margins, and so are provided for illustrative purposes only – these values should not be used in designing an optical system and/or specifying filter requirements

1) Spectral transition zone
    a. Allowed dead band (transition from T>95% to R>98%): 1560nm to 1545nm → **15 nm**
        i. This sets the total wavelength budget available
2) Operating temperature range
    a. Tc ~20 pm/C, temperature range -40C to 80C
        i. Wavelength shift over temperature range: ~**2.4 nm**
3) Operating AOI range
    a. AOI range from 20 deg to 25 deg (ie 22.5 +/-2.5deg):
        i. Wavelength shift over AOI range: ~**11 nm**
4) Polarization
    a. Single polarization
        i. Wavelength shift to account for polarization: **0 nm**
5) Source variation
    a. Variation due to uncertainty in the two sources: **~0.2nm**
6) Filter design
    a. Design curve slope from T>95% to R>98%: ~**3.0 nm**
7) Wavelength targeting
    a. Manufacturing margin for wavelength targeting: ~**0.2 nm**
8) Coating non-uniformity
    a. Manufacturing margin for uniformity: ~**1.5 nm**

Sum of the "application influenced" wavelength budget consumers:

Temp range (2) + AOI range (3) + Polarization (4) + Source (5) = 2.4 + 11 + 0 = 0.2 = ~**13.6 nm**

Sum of the "filter manufacturing influenced" wavelength budget consumers:

Design (6) + Targeting (7) + Non-uniformity (8) = 3.0 + 0.2 + 1.5 = ~**4.7 nm**

Total wavelength budget required: 13.4 + 4.7 = ~**18.3 nm**

Total budget available (1): **15 nm**

As the wavelength budget required by the application and filter manufacturing considerations exceeds by more than 3 nm the budget available from the desired dead-band this filter is, as specified, unmanufacturable.

In order to come up with a manufacturable solution application trade-offs would be necessary such as reducing the AOI range or nominal AOI or moving the defined transmission and reflection wavelength points further apart. The filter manufacturer could try to reduce some of the manufacturing margins but these are already small contributions to the budget so there is little to be gained (and any gains would need to come with higher costs due to increased manufacturing complexity and risks of requiring repeated runs).

The two optical system design parameters that most frequently may be adjusted to have the biggest benefit on reducing the wavelength shift within the filter dead-band are:

a) AOI and AOI range:
    a. This is a physical parameter that may be modified at time of system design and often can have the largest impact on wavelength budget; either by reducing the nominal working AOI or by locating the filter in a more collimated part of the beam.
b) Filter useable aperture dimensions:
    a. The coating non-uniformity spec is a function of the spatial area over which the spectral performance must be maintained. By either reducing the size of the filter or by only specifying the performance over the beam area within a larger physical size the functional effect of non-uniformity may be minimized. Specifying performance where it is not functionally needed unnecessarily increases complexity and cost.

Conclusion

As in day to day life, we need to set and live within our budget when designing and manufacturing filters. It is best to engage with the filter design and manufacturing team as early as possible in the system design process to ensure that system design constraints are compatible with filters that can be manufactured in practice.