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Calculating laser eyewear effective OD and VLT using manufacturer OD curves.

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Abstract

Spectral bandwidth (SB) of ultrashort laser pulses (under 100 fs) in commonly used near-IR range can be tens of nanometers. When selecting laser eyewear for use with ultrashort pulses, the "effective" optical density (OD_{eff}) should be calculated from a convolution of the spectral curve for the filter transmission with the spectrum of the laser pulse. We present model calculations of OD_{eff} curves (OD_{eff} versus wavelength) for selected commercial eyewear filters at different pulse durations, assuming a gaussian laser spectrum.

Visible light transmission (VLT) is another important laser eyewear characteristic. We use the definition for photopic luminous transmission in the Z136.7-2008 standard to calculate VLT values by convoluting the manufacturer transmission curves with the photopic luminous efficiency function and the spectrum for a CIE Standard Illuminant D source that approximates average daylight over the visible range. We then compare the calculated VLT with what the manufacturers provide and with "lab VLT" measurements that we have made using a light meter and a source provided by standard lab fluorescent or LED lighting.

Introduction

Ultrashort laser pulses (under 100 fs) in near-IR range have spectral bandwidth (SB) of tens of nanometers (for example, at 800 nm a laser pulse of τ_p = 30 fs duration has a FWHM spectral bandwidth of approximately 30 nm; for τ_p = 10 fs, it is 94 nm). Meanwhile, the optical density of eyewear is wavelength-dependent:

$$OD(\lambda) = -\log T(\lambda), \tag{1}$$

where T is the transmittance of the material. The spectrum of a laser pulse normally peaks at the center wavelength (e.g. 800 nm for a typical Ti:Sapphire system) but portions of the spectrum far from the center wavelength can still carry significant energy. Since the actual laser spectrum "probes" the filter transmittance not only at its central wavelength but over the entire transmittance spectral range, the manufacturer specified OD at a single wavelength does not accurately represent the protection provided by the filter for a short pulse hazard. We calculate the "effective" OD by convoluting the filter transmittance $T(\lambda)$ with the laser emission spectrum to quantify the effect of laser bandwidth on the effective OD.

Our study of VLT was motivated by discrepancies observed between the values of our measured VLT for several commercially available laser eyewear filters and the values specified for those by the manufacturers. We calculated VLT for several filters following the procedure outlined in the American National Standard for Testing and Labeling of Laser Protective Equipment ANSI Z136.7 and compared with the manufacturer-specified numbers and our measurements.

Effective optical density OD_{eff}

For this model study, we assumed a Gaussian laser spectrum G (λ_c; $\Delta\lambda$) determined by the central wavelength λ_c and the spectral bandwidth $\Delta\lambda$. Using Equation (1), transmission is: $T(\lambda) = 10^{-OD(\lambda)}$. It has to be weighted with the Gaussian G (λ_c; $\Delta\lambda$) spectral curve and then OD_{eff} can be calculated as:

$$OD_{eff} = -\log_{10} \frac{\int 10^{-OD(\lambda)} \mathrm{G}(\lambda_c;\Delta\lambda) d\lambda}{\int \mathrm{G}(\lambda_c;\Delta\lambda) d\lambda} \tag{2}$$

Expression (2) for OD_{eff} was used to evaluate the effective optical density numerically:

$$OD_{eff} = -\log_{10} \frac{\sum_\lambda 10^{-OD(\lambda)} \mathrm{G}(\lambda_c;\Delta\lambda)}{\sum_\lambda \mathrm{G}(\lambda_c;\Delta\lambda)} \tag{3}$$

for selected commercial eyewear filters at pulse durations of 30 fs and 15 fs. Assuming a Gaussian time profile of the pulse, the time-bandwidth product is $\Delta f \tau_p \cong 0.44$, so the spectral bandwidth is given by:

$$\Delta\lambda \cong \frac{\lambda_c^2}{c} \frac{0.44}{\tau_p}. \tag{4}$$

The numerical procedure for calculating OD_{eff} in the approximation of a Gaussian spectrum of laser emission is given in Appendix A.

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OD_{eff} (λ) curves for filter #8 for 30 fs and 15 fs pulse durations are shown in Figure 1 along with the manufacturer's OD curve. It can be seen that OD_{eff} varies from 2 to 6 in the spectral range from 760 nm to 840 nm which is accessible with most mode-locked Ti:Sapphire systems. At the same time, the manufacturer's OD is close to 7 almost everywhere in that range.

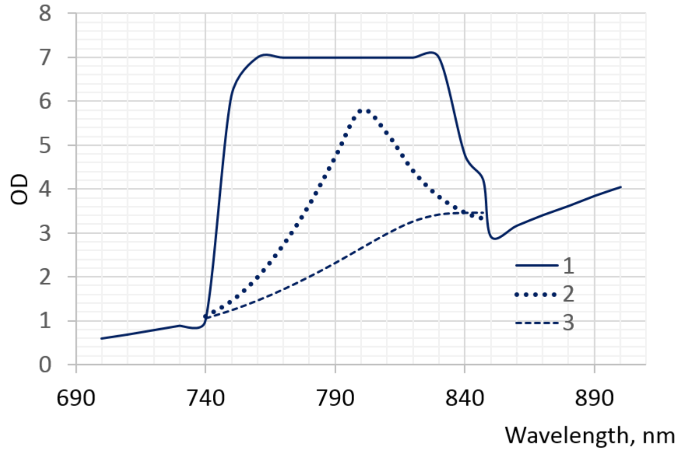

Figure 1. Filter #8. (1) manufacturer OD values; OD eff calculated for: (2) 30 fs pulse; (3) 15 fs pulse.

Similar analysis for other commercially available filters is shown in Figures 2 and 3 for 30 fs pulses (eight filters have been analyzed). For shorter emission wavelengths, the spectral bandwidths for the same pulse duration are smaller (per Equation 4), so the effect is not as pronounced (see Figure 3).

The effects of the short laser pulse spectral composition on the OD cannot be ignored when selecting a proper eyewear. The effective OD needs to be evaluated for the particular wavelength hazard, eyewear transmission curve, and pulse duration.

Gaussian approximation for the laser spectrum is a good starting point and can be done using the procedure in Appendix A. For the sources with output spectrum far from Gaussian, the actual spectral distribution should be used.

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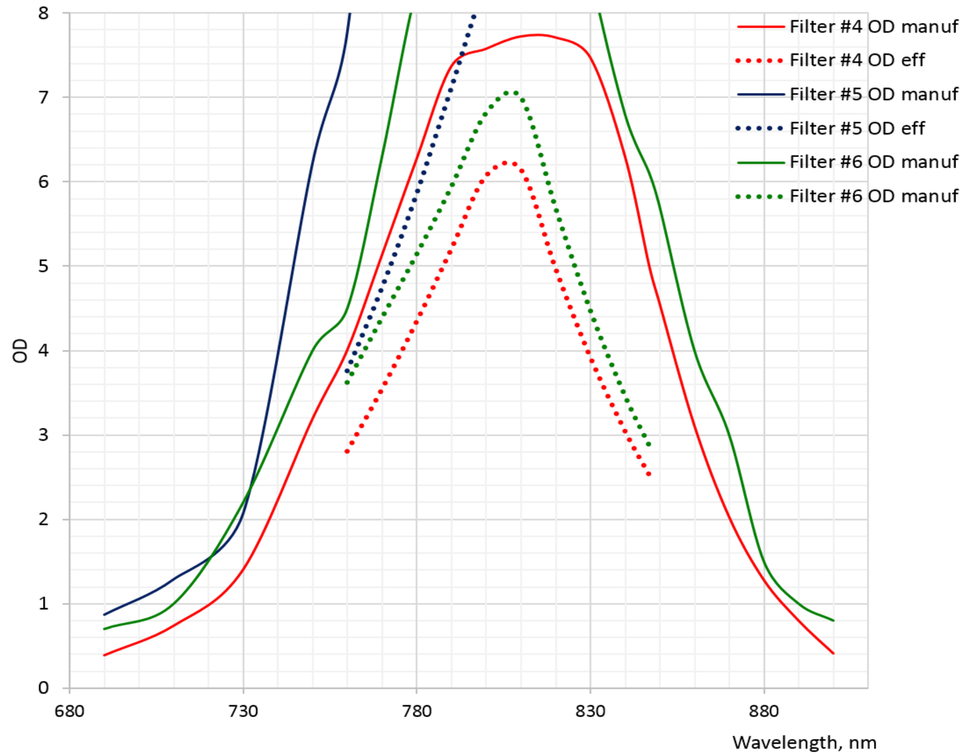

Figure 2. Manufacturer and effective optical densities for commercially available laser eyewear filters #4, #5, and #6 for a 30 fs pulse centered around 800 nm.

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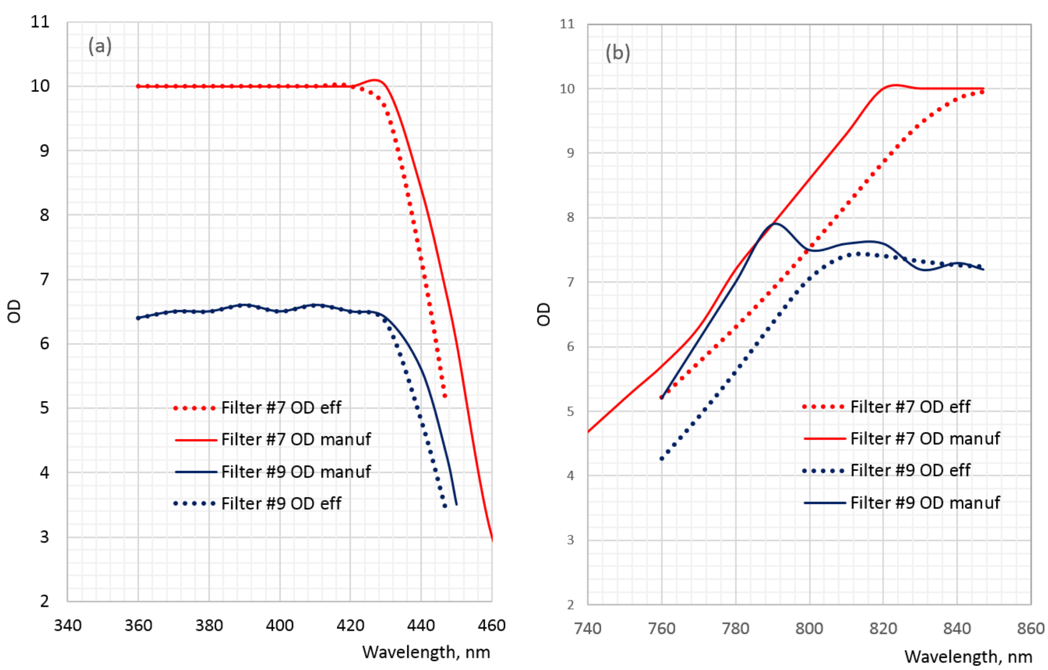

Figure 3. Manufacturer and effective optical densities for commercially available laser eyewear filters #7 and #9 for a 30 fs pulse centered around: (a) 400 nm; (b) 800 nm.

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Calculation of visible light transmission VLT for commercially available eyewear filters

Visible light transmission (VLT) is another important characteristic of laser eyewear. Low VLT can frustrate laser workers when performing tasks that require fine vision. That may reduce their productivity and become a reason for removing eyewear, or peeking, which has led to injury accidents in the past. Therefore, it is vital to have a correct estimate of VLT when selecting the laser eyewear.

We use the definition for photopic luminous transmission in the ANSI Z136.7-2008 standard [2]:

$$VLT_{phot} = \frac{\sum_{\lambda} S_{\lambda} V_{\lambda} T_{\lambda}}{\sum_{\lambda} S_{\lambda} V_{\lambda}} \qquad (5)$$

where T_λ is the eyewear filter transmission specified by the manufacturer, S_λ is the spectrum for a CIE Standard Illuminant C source that approximates average daylight spectral composition over the visible range, and V_λ is the photopic luminous efficiency function characterizing the human eye's ability to perceive light at different wavelengths. We then compare the calculated VLT with the manufacturer specified values and with VLT measurements we have made using a BK Precision 615 lightmeter and a standard lab source of fluorescent or LED lighting (Figure 4).

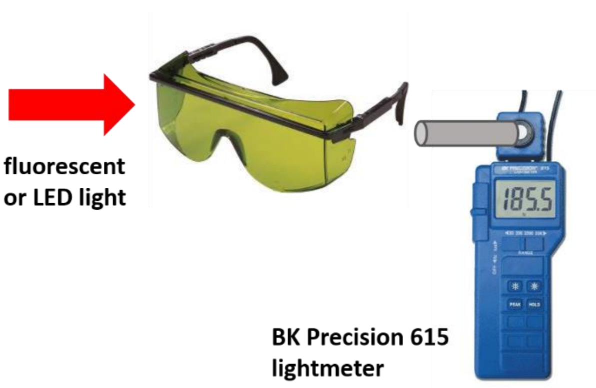

Figure 4. Set-up for measurement of the VLT for fluorescent or LED lighting using BK Precision 615 lightmeter.

The illuminance for ambient lighting I_{amb} and when transmitted through an eyewear filter I_{trans} have been measured and the value of VLT obtained with:

$$VLT_{meas} = \frac{I_{trans}}{I_{amb}} x100\% \qquad (6)$$

Table 1 contains a summary of the calculated and measured VLT values compared with the manufacturer specified VLT. The details of the calculation are summarized in Appendix B.

Table 1. VLT for commercially available laser eyewear filters calculated with Equation (5) using the photopic luminous efficiency function and the spectrum for a CIE Standard Illuminant C source. The measured values have been obtained using a fluorescent source of lighting.

Filter #	VLT calculated, %	VLT measured, %	VLT manufacturer, %
1	16.4	22	23
2	17.6	13	22
3	26.3	-	33
4	50.4	-	49
5	56.2	-	60
6	34.4	41	45
7	22.3	18	32
8	57.7	-	75
9	37.0	36-38	45
10	18.6	-	17.3

The spectral transmittance curves provided by the eyewear manufacturers and the CIE C Standard Illuminant source spectral intensity used in the calculation summarized in Table 1 are shown in Figure 5.

All measured values of VLT (obtained for five filters) fall below the manufacturer specified numbers and all except two – for filters #4 and #10 – calculated values are below the manufacturer's data. Calculations with Formula (5) were also done using a "unity" source (S_λ = 1); we found that these VLT_{phot} values were within 1% of those obtained with a CIE Standard Illuminant C source.

In an attempt to understand the reason for the discrepancy, we calculated VLT for one of the filters (#2) with the spectra of two sources that were used for the measurement – fluorescent and LED (Figure 5 (b)). The values are close to those obtained with the CIE C source (17.6%) and the unity source (18.5%): 18.1% (fluorescent source) and 20.3% (LED source), so do not explain the disagreement between the measurements and the calculations.

Looking for possible reasons for the discrepancy between the calculated values and the measurements

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with BK Precision 615 we tested the accuracy of the correction for the photopic luminous coefficient in the instrument. We verified the performance with three laser sources at visible wavelengths: 405 nm, 532 nm, and 639 nm and attempted to calibrate it in absolute scale of illuminance (lux). The laser power P_λ was measured and the illuminance calculated with:

$$I\ [\text{lux}] = 683\ P_\lambda\ V_\lambda\ /\ A\ [\text{m}^2] \qquad (7)$$

where V_λ is the photopic luminous efficiency coefficient for the wavelength λ and A is the sensor area. At 405 nm the agreement between the light-meter measurement and the illuminance obtained with (7) was at 10% level, but it deteriorated to 47% at 532 nm and 60% at 639 nm. We are trying to further investigate the features of the instrument design with the vendor company while exploring other options for measuring the illuminance.

From the calculation standpoint, this issue needs to be studied further to understand the eyewear manufacturers' methods of obtaining the VLT values and the reasons for the discrepancy between our results. A desirable outcome of this analysis and discussion would be establishing a common approach to determining VLT across the laser safety eyewear industry.

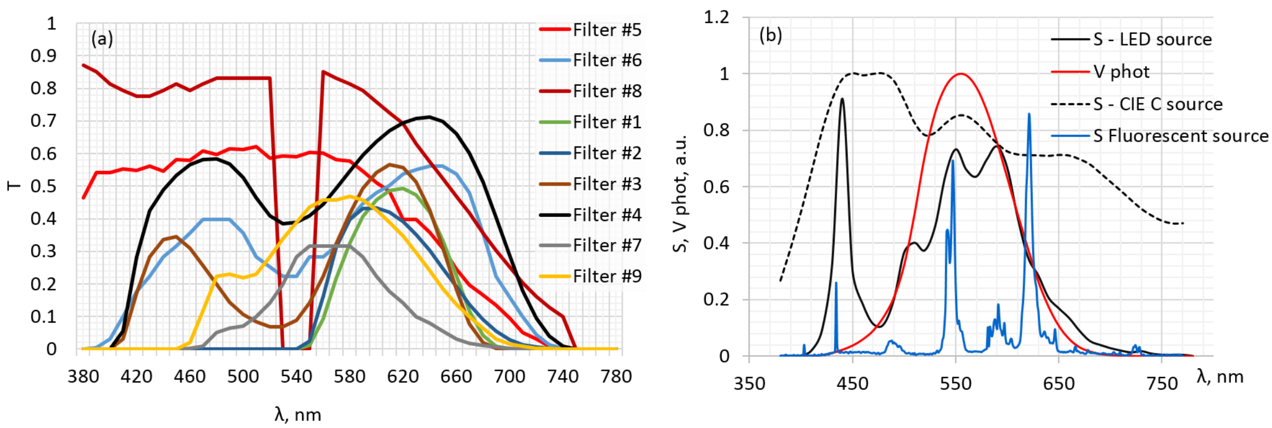

Figure 5. (a) Manufacturer spectral transmittance curves for commercially available laser eyewear filters; (b) CIE C Standard Illuminant source spectral intensity, spectra of fluorescent and LED light sources, photopic luminous efficiency curve.

Conclusion

In conclusion, we find:

a) The OD_{eff} values obtained by convoluting the transmission spectral curves with the model Gaussian spectra of laser emission show that there is an overall reduction in OD for pulses with tens of nanometers bandwidth. The practical outcome is that when selecting laser protection eyewear for ultrashort (under 100 fs) laser pulses the effective OD should be evaluated to make sure that the filter provides adequate protection against the hazard. We provide a numerical procedure for calculating OD_{eff} using widely available Microsoft Office tools.

b) Visible light transmission (VLT) specified by manufacturers for a number of commercially available laser eyewear filters was found to deviate from our calculations that followed the ANSI Z136.7 prescription. Laser eyewear manufacturers should review and provide information on how their VLT specifications are determined. A common approach for VLT calculations, such as that provided in Z136.7, is needed.

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References

1. American National Standard for Safe Use of Lasers. ANSI Z136.1 – 2014.
2. American National Standard for Testing and Labeling of Laser Protective Equipment. ANSI Z136.7 – 2008.

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Meet the Authors

Igor Makasyuk, CLSO, has a background in laser physics, optics, spectroscopy, atomic and molecular processes. He received his Ph.D. in Physics and M.S. in Physics from the University of St-Petersburg (Russia). He conducted research with lasers in several countries including development of tunable laser sources and laser applications at Stanford University. After joining SLAC, Igor Makasyuk worked in the field of laser applications for accelerating electrons and ultra-high resolution electron diagnostics of matter. He is an author of over sixty publications in peer-reviewed journals and conference submissions. Igor Makasyuk is a CLSO serving as SLAC Deputy Laser Safety officer since 2016. He is a member of DOE’s EFCOG Laser Safety Task Group.

Michael Woods, CLSO, is the Laser Safety Officer at SLAC. He is an Engineering Physicist, with a B.Sc. in Engineering Physics from Queen's University in Kingston, Ontario, Canada and a Ph.D. in High Energy Physics from the University of Chicago. He has spent 15 years as a researcher in experimental particle physics and accelerator physics, utilizing high power laser systems for photo-injectors, Compton polarimeters and electron beam diagnostics. He became SLAC LSO in 2008. He is a member of the ANSI Z136 ASC, ADCOM, SSC-1, SSC-8and TSC-5 committees and is chair of TSC-4.

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APPENDIX A.

The numerical calculation with Equation (3) can be done using any software available. In the example below, we show how Microsoft Excel can be used to calculate OD_{eff} for a filter with the manufacturer specified dependence OD(λ) in the range of wavelengths from 600 to 1000 nm, the laser spectrum centered at 800 nm, and the pulse duration of 30 fs.

Table A1. Calculation of OD_{eff} using Microsoft Excel assuming Gaussian laser emission spectrum for a 30 fs laser pulse centered at 800 nm.

	A	*B*	C	D	E	F	G	H	I
1	λ, nm	λ_c, nm	$\Delta\tau_p$, fs	$\Delta\lambda$ (SB), m	OD(λ)	$10^{-OD(\lambda)}$	*G* (λ_c, $\Delta\lambda$)	*G* (λ_c, $\Delta\lambda$) *10-OD(λ_c)	OD eff
2	Row 2 was intentionally left blank.								
3	600	800	30	3.13E-08	3.7E-01	4.27E-01	6.34E-50	2.70E-50	**7.062E+00**
4	610				4.1E-01	3.89E-01	3.97E-45	1.54E-45	
5	620				4.6E-01	3.47E-01	1.41E-40	4.89E-41	
…	…	…			…	…	…	…	
22	790				7.9E+00	1.26E-08	7.53E-01	9.48E-09	
23	800				7.5E+00	3.16E-08	1.00E+00	3.16E-08	
24	810				7.6E+00	2.51E-08	7.53E-01	1.89E-08	
…	…	…			…	…	…	…	
42	990				7.6E+00	2.51E-08	3.97E-45	9.97E-53	
43	1000				7.6E+00	2.51E-08	6.34E-50	1.59E-57	
44						**SUM**	**3.331E+00**	**2.884E-07**	

1. Column A (A3:A43 in this example): enter the full range of wavelengths for which the OD(λ) of the filter is known (obtained from the manufacturer).
2. B3 = λ_c – the wavelength where the laser spectrum is centered (800 nm in this example).
3. C3 = $\Delta\tau_p$ – the pulse duration in fs (30 fs in this example).
4. D3: =(B3*1E-9)^2/3E8*0.44/(C3*1E-15) – calculation of the bandwidth SB $\Delta\lambda$ with Equation (4).
5. Column E (E3:E43 in this example) contains the manufacturer's values of OD(λ).
6. Column F (F3:F43): calculation of the transmittance of the material using Equation (1): F3: =POWER(10,-E3) - propagate to F43.
7. Column G (G3:G43): calculation of the Gaussian function reduced to a Gaussian wavelength dependent factor (relationship (A3) below). The laser emission spectrum is assumed to be given by the Gaussian function in the form:

$$G(\lambda_c, \Delta\lambda) = \frac{1}{\sqrt{2\pi}\sigma_\lambda} exp\left[-\frac{1}{2}\left(\frac{\lambda-\lambda_c}{\sigma_\lambda}\right)^2\right]$$
(A1)

where σ_λ is the standard deviation. Bandwidth $\Delta\lambda$ in Equation (4) is a FWHM (full width at half-maximum) value for the Gaussian spectrum, which relates to the standard deviation through:

$$\sigma_\lambda = \frac{\Delta\lambda_{FWHM}}{2\sqrt{2ln2}} \qquad \text{(A2)}$$

Taking into account that the coefficients in front of the exponent in (A1) do not depend on wavelength and will cancel out in the final calculation of OD_{eff} with Equation (3), we can operate with just the wavelength dependent exponential part where standard deviation has been replaced with the bandwidth using (A2):

$$G(\lambda_c, \Delta\lambda) \propto exp\left[-\frac{1}{2}\left(\frac{\lambda-\lambda_c}{\Delta\lambda_{FWHM}} 2\sqrt{2ln2}\right)^2\right]$$
(A3)

and

$$\Delta\lambda_{FWHM} \cong \frac{\lambda_c^2}{c}\frac{0.44}{\tau_p}. \qquad \text{(A4)}$$

The input in G3 to calculate the Gaussian factor with (A3) where $\Delta\lambda_{FWHM}$ is calculated in D3 is:
G3 = EXP(-0.5*((A3-B3)*1E(-9)*2*SQRT(2*LN(2))/D3)^2).
(the wavelength values in column A and cell B3 are converted to m).

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8. Column H (H3:43): multiply the transmittance by the Gaussian factor:
9. H3 = F3*G3 (propagate down the table).
10. Calculate the sum of $G(\lambda_c, \Delta\lambda)$ over all wavelengths:
    G44 = SUM(G3:G43).
11. Calculate the sum of $G(\lambda_c, \Delta\lambda)10^{-OD}$ over all wavelengths:
    H44 = SUM(H3:H43).
12. Calculate OD_{eff} with Equation (3):
    I3 = - LOG(H44/G44).

    In this example (800 nm, laser pulse 30 fs), the effective OD of the filter at the central wavelength of the laser emission is equal to 7.062.

APPENDIX B.

The calculation of photopic VLT follows the procedure outlined in ANSI Z136.7 [2], Appendix A. We briefly summarize it here and provide more detail on using Microsoft Excel, input in fields, etc.

V_λ = photopic luminous efficiency function (CIE 1951 standard, found in Table A1, ANSI Z136.7, Appendix A);

T_λ = spectral transmittance of the filter material (provided by the manufacturer; if OD is provided, see the example in table below);

S_λ = spectral intensity of source (typically CIE C – average daylight – CIE 1951 standard; found in Table A1, ANSI Z136.7, Appendix A);

Table B1. Calculation of VLT_{phot} using Microsoft Excel assuming spectral intensity of source as CIE C – average daylight – CIE 1951.

	A	B	C	D	E	F	G
1	**Wavelength λ, nm**	***OD_λ***	***T_λ***	***S_λ***	***V_λ***	**S_λ x V_λ**	**S_λ x V_λ x T_λ**
2	380	0.06	0.8710	33	0	0	0
3	390	0.07	0.8511	47.4	0.0001	0.0047	0.0040
4	400	0.09	0.8128	63.3	0.0004	0.0253	0.0206
	…	…	…	…	…	…	…
40	750	6.12	7.59E-07	59.2	0.0001	0.0059	4.49E-09
41	760	7	1E-07	58.1	0.0001	0.0058	5.81E-10
42	770	7	1E-07	58.2	0	0	0
43	780	7	1E-07	0	0	0	0
44					**SUM**	**1064.7**	**614.6**

Inputs in the Excel table are as follows:

1. Column A: wavelengths.
2. Column B: if the spectral transmittance T_λ is available from the manufacturer, skip column B and enter T_λ in column C. If only OD_λ is available, enter it in column B.
3. Column C: calculate T_λ from OD_λ by inputting:
   C2: "=POWER(10,-B2)" and propagating down the table.
4. Column D: to use the spectral intensity CIE C – average daylight – enter it from the corresponding column in Table A1 in ANSI Z136.7, Appendix A for all wavelengths.
5. Column E: enter V_λ - the photopic luminous efficiency function (CIE 1951 standard, found in Table A1, ANSI Z136.7, Appendix A).
6. Column F: multiply S_λ x V_λ for each wavelength by inputting:
   F2: "=D2*E2" and propagating down the table.
7. Column G: multiply S_λ x V_λ x T_λ for each wavelength by inputting:
   G2: "=F2*C2" and propagating down the table.
8. Calculate separate totals (sums) for all products (columns F and G in the table):
   F44: "=SUM(F3:F43)". In the example above: 1064.7.
   G44: "=SUM(H3:H43)". In the example above: 614.6.
9. Calculate VLT_{phot} with Equation (5). In the example above: VLT_{phot} = 614.6/1064.7 (x 100%) = 0.577 (x 100%) = 57.7%.

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