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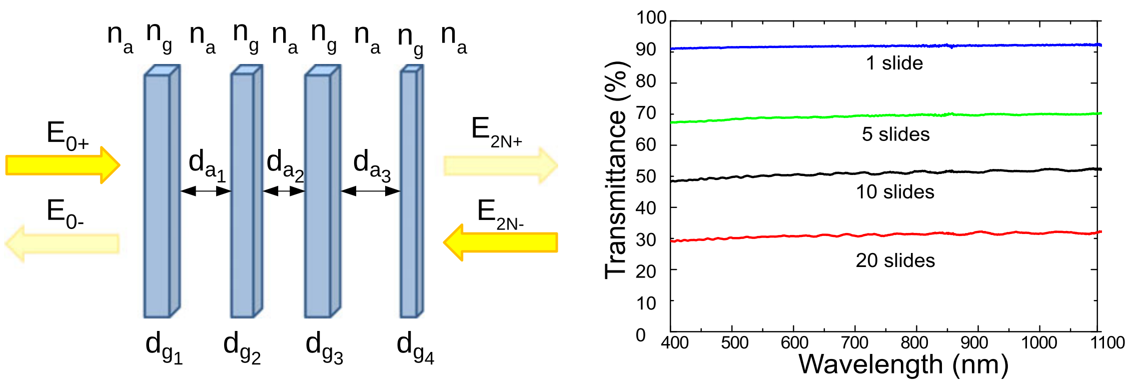

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Durable and Cost-Effective Neutral Density Filters Utilizing Multiple Reflections in Glass Slide Stacks

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Abstract: We propose an application of a stack of glass slides as a broadband neutral density filter with high (> 100 W/cm^2) damage threshold. The influence of multiple reflections on the filter transmittance is analyzed with transfer matrix method. The numerical study proves that the filter spectrum is determined by material dispersion and degree of wavelength averaging occurring due to light incoherence and limited measurement resolution. Varying the angle of light incidence can be used to extend the possible optical density range of the filters. The numerical results are verified by spectral measurements with setups containing coherent and incoherent light sources. The applicability of the filters is proven in a concentrated sun simulator.

Index Terms: Optical filters, refractive index, optical scattering, dielectrics.

1. Introduction

Neutral density (ND) filters enable control of light intensity by absorption or reflection of incident light without modifying its spectrum. These optical components are used when excessive power might cause damage to detectors or other components or for artistic purposes in photography. Typically, ND filters are composed of an absorbing layer or a thin metal film deposited on a glass substrate for absorptive or reflective ND filters, respectively. Yet, in optical setups that require large intensities of light (e.g. concentrator solar simulators, laser systems) such filters can be damaged due to evaporation of metal (reflective ND filters) or due to cracking of the filter as a result of excessive heat absorption (absorptive ND filters). Additionally, the filters suffer from excessive variation of transmittance with increasing optical density.

The central idea of our work is that instead of using a single absorbing or reflecting surface to filter light, multiple layers with alternating refractive indices and random thicknesses may be used to reduce intensity by multiple reflections within the structure. This enables using materials with lower dispersion and higher damage threshold (e.g. glass) to obtain a flat transmission spectrum.

The transmittance of a stack of glass slides (see Fig. 1) has been studied theoretically for a long time and the observation that an increased number of interfaces reduces the system transmittance

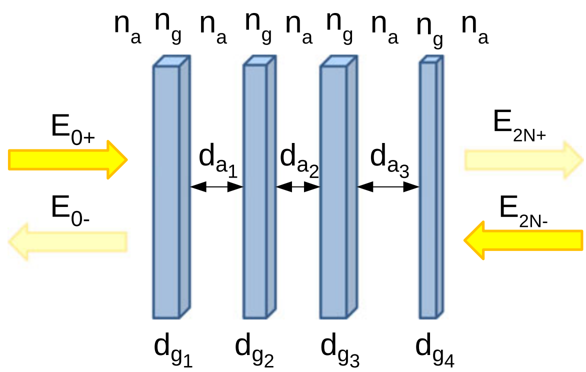

Fig. 1. Glass ND filter composed of 4 glass slides and air gaps in between.

dates back to Stokes (the theory is revised thoroughly in Tuckermann's article [1]). Further investigations have proven that as a result of interference of multiply reflected waves localization of light can occur in one-dimensional multilayers with disorder and this phenomenon has been studied theoretically [2], [3]. Berry and Klein [4] have suggested a correspondence between localization of light in a system composed of thin plastic plates with an analogous electronic phenomenon [5] and found the dependence between transmittance and number of plates. Our numerical results are an extension of what has been done in [6]. The authors have noticed that it may not be possible to resolve fine-scale transmittance fluctuations and therefore averaging of transmittance over appropriate bandwidth shall be applied to approximate realistic transmission measurements.

The localization of light has been observed experimentally in various one dimensional systems. One class of such systems are disordered photonic crystals (e.g. TiO_2-SiO_2 Bragg reflectors [7] and grooved Si one-dimensional photonic crystals [8]), where the introduction of disorder results in broadening of the high reflection range. The phenomenon has been studied numerically for Bragg reflectors with disorder and inhomogeneity for TE and TM polarizations and various angles of incidence. The broadening of the high reflectance spectral region has been observed when disorder is introduced for both s- and p-polarized light in a broad range of angles of incidence [9]. Further control over dependence of transmittance on polarization and angle of incidence may be gained by using birefringent materials [10]. Localization of light in Bragg reflectors can result in a flat spectrum in a broad wavelength range, but only for reflectance approaching unity, so the resulting device can be used as an extremely good broadband mirror, but not as an ND filter.

On the other hand, there have been multiple reports of experimental measurements of transmittance and observations of light localization in systems with properties resembling the stack of glass slides separated by thin air gaps: thin plastic films separated by air gaps [4], scatterers in a waveguide tested with various spatial distributions [11] or randomly distributed gratings in an optical fiber [12]. In these reports, narrowband coherent light sources have been used to prove Berry-Klein (BK) theory. In [6] a similar experiment has been performed with a device with lower spectral resolution using a stack of glass slides and neither the results of BK theory nor of Stokes theory have been reproduced. The authors attributed this deviation from theory to the inability to resolve fluctuations arising from high degree of disorder and show that theoretical calculations match qualitatively the experimental results, when they are linearly averaged over wavelength.

We extend this previous work by considering that suppression of fluctuations due to disorder occurs not only as a result of insufficient resolution but also as a result of dephasing of light propagating within the glass stack. Decoherence might be observed as a result of surface imperfections or impurities as well as light source incoherence. We show the equivalence of averaging of transmittance over wavelength presented in [6] and random phase averaging used for treating partial coherence of light in transfer matrix method simulations. The observation that decoherence suppresses random fluctuations in transmission spectra leads to the idea of using glass slide stacks as broadband neutral density filters with tailored optical density and a damage threshold over 100 W/cm^2, which is higher than for previously known ND filters. The influence of glass dispersion and angle of light incidence is analyzed based on numerical simulations. The analysis is verified with experimentally measured transmission spectra with various optical setups and both broadband flat transmittance and high damage threshold are observed. As an exemplary application of our ND filters, we show the capability to control the intensity of a 1000 W Xe lamp in a concentrated sun simulator enabling reliable solar cell testing upon both high and low intensity conditions.

2. Numerical Analysis of Filter Properties

2.1 Influence of Multiple Reflections

The transfer matrix method from [13] is used for numerical calculations. The electric fields resulting from forward and backward wave propagation are linked by the transfer matrix M_N, where N denotes the total number of glass slides. M_N is calculated as a product of transmission matrices (D_{ij}, see (2)), which are relating the electric field between left and right hand side of a medium boundary between ith and jth layer, and propagation matrices ($P_{m,i}$, see (3)). We assume that the incident and exit medium is air and the structure is composed of alternating air and glass layers. Therefore, the product takes the following form (s indexes the glass slides):

$$\begin{bmatrix} E_0^+ \\ E_0^- \end{bmatrix} = \underbrace{\left(\prod_{s=1}^{N} D_{A_{s-1}G_s} P_{G_s} D_{G_s A_s} P_{A_s}\right)}_{M_N} \begin{bmatrix} E_{2N}^+ \\ E_{2N}^- \end{bmatrix}. \tag{1}$$

The transmission matrices are calculated based on transmission (t_{ij}) and reflection (r_{ij}) coefficients for forward and backward propagation of light through the boundary:

$$D_{ij} = \frac{1}{t_{ij}} \begin{bmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{bmatrix}, \tag{2}$$

while propagation matrices depend on the phase factor, which is a product of refractive index (n_m, where m denotes the material type of the ith layer), wavenumber for light propagating through the ith layer ($k_{m,i}$) and its thickness ($d_{m,i}$):

$$P_{m,i} = \begin{bmatrix} \exp(i n_m k_{m,i} d_{m,i}) & 1 \\ 1 & \exp(-i n_m k_{m,i} d_{m,i}) \end{bmatrix}. \tag{3}$$

The thickness of each layer ($d_{m,i}$) is drawn from a random distribution. For glass slide thicknesses, a Gaussian distribution with average μ_G and standard deviation σ_G is used. Air gap widths are distributed uniformly, since we could not measure such small distances with sufficient precision. The minimal air gap width is 10 μm, while the maximal air gap width is 60 μm.

The transmittance of a stack containing N layers is given by M_{N22}^{-1}, the inverse of the bottom right element of matrix M_N. However, as a result of partial light coherence (for instance, due to surface imperfections) and finite measurement resolution, averaging of transmittance over a wavelength range $\Delta\lambda$ occurs [6]:

$$\tau_N(\lambda) = |t_N(\lambda)|^2 = \int_{\Delta\lambda} |[M_N(\lambda)]_{22}^{-1}|^2 \frac{d\lambda}{\Delta\lambda}. \tag{4}$$

Layer thickness and wavelength (by being inversely proportional to k) contribute to the phase factor of propagation matrix $P_{m,i}$ in (3). Therefore, averaging of transmittance with random layer thicknesses over wavelength is equivalent to averaging over random phase factors introduced into the propagation matrices (provided that the glass has low dispersion - the case of dispersive glass is described in the next section). It has to be noted that for multilayers containing multiple transparent layers full linear averaging over all phase values does not yield the same result as replacing all transmission and reflection coefficients with their amplitudes squared [14].

The two analytic predictions of transmittance as a function of number of layers made by Berry and Klein [4] (see (5)) and by Stokes [1] (see (6)) are the limiting cases for non-absorbing layers. With

TABLE 1
Typical Set of Parameters Used in Simulation

Parameter name	Parameter symbol	Parameter value
minimal air gap (μm)	–	10
maximal air gap (μm)	–	60
mean glass thickness (μm)	μ_G	170
std. deviation of glass thickness (μm)	σ_G	3
refractive index of glass	n_G	1.54

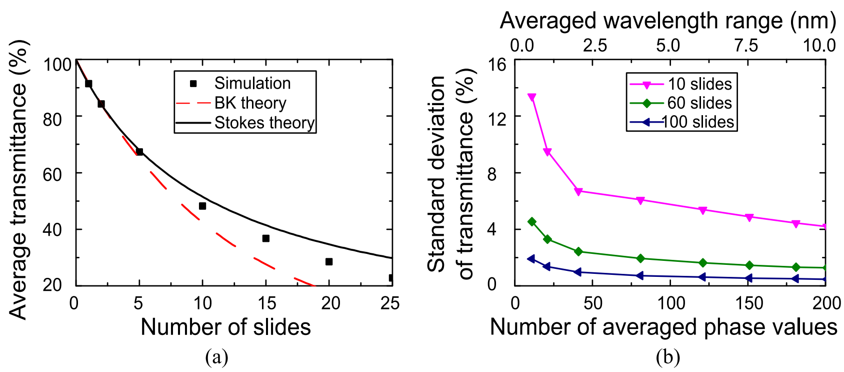

Fig. 2. Transmittance of a stack of glass slides with constant refractive index $n = 1.54$: a) average transmittance as a function of number of slides - comparison of simulation with linear averaging over 700 phase values with previously known theoretical results, b) standard deviation of transmittance as a function of number of averaged phase values for various number of slides.

no absorption, the reflection and transmission for backward and forward propagation are related by Stokes relations and the properties of the transfer matrix M_N can be studied analytically [3]. The log-averaged transmittance of a stack containing N glass slides takes the form predicted by Berry and Klein:

$$\tau_N = \exp\left(-N \log(1/\tau)\right) \tag{5}$$

for coherent light propagation in a limit of high number of interfaces [4] (multiple reflections cancel out by destructive interference). BK theory may not be correct when fine-scale fluctuations are not observed or suppressed. This may occur due to the use of incoherent light sources or surface imperfections.

Another analytic prediction for a stack of N glass slides is the result obtained by Stokes

$$\tau_N = \frac{\tau}{\tau + N(1-\tau)} \tag{6}$$

for incoherent light propagation. Stokes result can be reproduced by considering intensities rather than amplitudes in the transfer matrix M_N [1], [12]. We show that in our filters incoherent propagation does not occur and multiple reflections have to be considered.

Wavelength averaging enables finding the correct value of the glass ND filters' transmittance for broadband or partially coherent light sources, which are used in our experiments. A typical set of parameters used in our numerical analysis has been selected based on experimental data for our glass ND filters and is presented in Table 1. Different parameters are used when noted.

Fig. 2(a) compares Stokes and BK theory results to linearly averaged transfer matrix method simulation result. Additionally, the standard deviation of transmittance of the multilayer stack depends on whether fine-scale fluctuations occur or not. To assess how the bandwidth of transmittance averaging in (4) influences the transmission spectrum, we have analyzed the dependence between standard deviation and number of averaged phase values (see Fig. 2(b)). The transfer matrix has been sampled from 700 to 800 nm wavelength in steps of 0.025 nm and averaged with varying wavelength range. The numerical results prove that for a high degree of wavelength or phase averaging the transmission spectrum of glass ND filters is almost flat. On the other hand, when no averaging occurs the standard deviation of transmittance is large. With increasing number of slides the standard deviation decreases, but it has to be taken into account that the average value is also lower.

2.2 Influence of Dispersion

Except for the amount of phase averaging, the spectrum is shaped by dispersion of the glass slides. In this section we analyze the influence of dispersion on the glass ND filters' spectrum in the limit of high degree of wavelength averaging (negligible random fluctuations of transmittance). We assume that the absorption and scattering can be neglected for a reasonable single glass thickness, quality (low roughness and defects concentration) and number of slides. Despite the fact that these processes may deteriorate the filter quality, we have observed that in our experiment the glass slides have sufficiently high quality not to observe a considerable influence of imaginary part of refractive index on glass transmittance. The analyzed spectral range is 400-1100 nm in which most of the glass types absorb low amount of light [15].

The transmittance spectrum of a stack with dispersive glass is obtained by calculating phase-averaged transmittance at each wavelength with glass refractive index given by the relation between refractive index and wavelength. This corresponds to the case where fluctuations resulting from interference are fully suppressed and the deviation from flat spectrum results only from the material dispersion.

The Cauchy model is used to model dispersion, because it is a sufficient estimation for the 400-1000 nm range and its limited number of input parameters simplifies the analysis [16]. Instead of analyzing the spectrum as a function of parameters B and C, which cannot be easily interpreted, Abbe number (V) and refractive index (n_D) for a single wavelength (589.3 nm) value are used. The parameters B and C can be expressed by V and n_D and substituted in the expression for refractive index. Abbe number is the measure for the spectral independence of glass transmittance based on the refractive index at three wavelength values ($\lambda_D = 589.3$ nm, $\lambda_F = 486.1$ nm and $\lambda_C = 656.3$ nm). The Cauchy model with parameters expressed by the Abbe number and refractive index at 589.3 nm leads to the following equation for refractive index as a function of wavelength:

$$n(\lambda) = B + \frac{C}{\lambda^2} = n_D + \frac{n_D - 1}{V\left(\frac{1}{\lambda_F^2} - \frac{1}{\lambda_C^2}\right)}\left(\frac{1}{\lambda^2} - \frac{1}{\lambda_D^2}\right). \tag{7}$$

Firstly, we analyze the spectra of filters with 10 glass slides composed of various glass types. The average transmittance as a function of refractive index for filters with non-dispersive glass is presented in Fig. 3(a). An exponential function is fitted to the simulation results to generate a larger number of points. Using (7), a dispersion function can be generated and transmission spectra of dispersive filters are obtained by using transmission values from Fig. 3(a) for refractive index values taken from the dispersion function for each wavelength value (as described previously). Such procedure is performed for various V and n_D values. The relative standard deviation of transmittance as a function of wavelength is calculated for each of the spectra to assess the range of glasses that can be used in ND filters. The final result is the dependence between the relative standard deviation of transmittance and Cauchy model parameters - Abbe number and refractive index at 589.3 nm, as presented in Fig. 3(b). Regardless of parameter values, the relative standard deviation does not exceed 5.5%, which leads to the conclusion that the influence of dispersion on the 10 glass slide stack spectrum is sufficiently low for application as an ND filter. The deviation from flat spectrum is more evident for large refractive index and low Abbe number values.

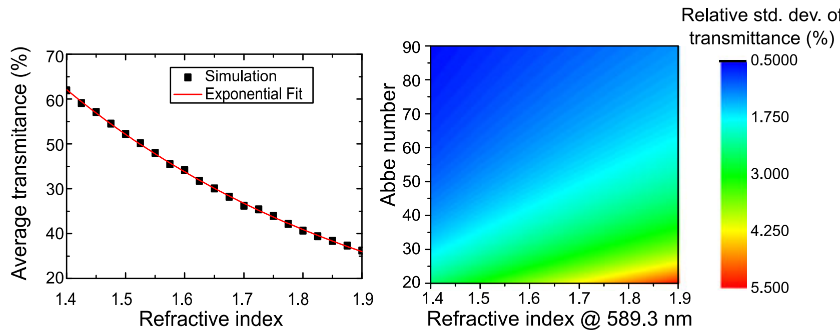

Fig. 3. Influence of dispersion on properties of a stack of 10 glass slides: a) average transmittance as a function of refractive index (non-dispersive glass), b) relative standard deviation of transmittance for dispersive glass with $n(\lambda)$ generated using the Cauchy model as a function of Abbe number (V) and refractive index at 589.3 nm (n_D).

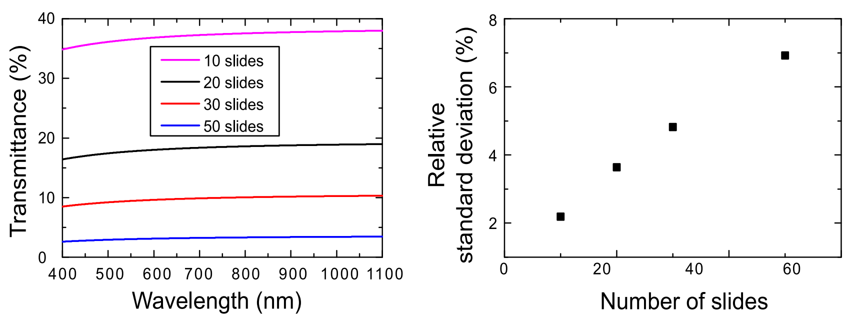

Fig. 4. Influence of dispersion on spectrum of glass ND filters: a) calculated spectra for filters with various number of slides, b) relative standard deviation as a function of number of slides. The slides are composed of a dispersive glass with $n(\lambda)$ generated using the Cauchy model with $n_D = 1.7$, $V = 40$.

A similar procedure can be performed for filters with various numbers of slides to analyze how the influence of dispersion on filter properties varies with the number of slides. The calculated spectra are presented in Fig. 4(a). Highly dispersive glass with low Abbe number and high refractive index ($V = 40$, $n_D = 1.7$) is used to make the influence of dispersion more pronounced. The standard deviation of transmittance over wavelength decreases with increasing number of slides. However, the average value decreases as well. Therefore, the relative standard deviation is calculated to assess how much the spectra deviate from flat transmission. The increasing relative standard deviation with increasing number of slides proves that the influence of dispersion is more pronounced for larger numbers of slides (see Fig. 4(b)).

2.3 Filter Transmittance for Oblique Incidence

Another important aspect of filter properties to be analyzed is the influence of oblique incidence on the filter transmittance. On one hand, many light sources emit light within a broad angular range, which must be taken into account when designing the filter. On the other hand, average transmittance can be controlled upon collimated illumination by modifying the angle of incidence (AOI) or tilting the filter. Based on Fresnel equations it is possible to calculate transmission and reflection coefficients in (2) for arbitrary AOI, which enables analysis of influence of oblique incidence. The analysis is performed for unpolarized light as we experimentally test the filters upon such illumination conditions.

As it is presented in Fig. 5, the filter transmittance as a function of angle differs for various number of slides. For a sufficiently large number of slides, an increase of transmittance with

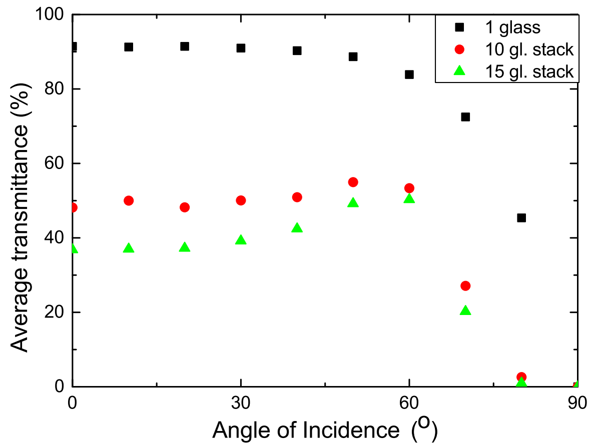

Fig. 5. Properties of glass ND filter with glass refractive index $n = 1.54$ for various angle of incidence (AOI) values: AOI dependence of average transmittance for filters with varying number of slides.

angle is observed below the Brewster angle. At the Brewster angle (approx. 60°) the transmittance value saturates and a further increase of AOI results in decrease of average transmittance. The influence of AOI is more pronounced for large numbers of slides. The influence of AOI on transmittance of a single glass plate is negligible below 30°. For polarized light, the angular dependence of transmittance is more pronounced and the values differ vastly for s and p polarization. The difference is maximum at the Brewster angle, which leads to a well-known application of glass slide stacks as so-called ”pile-of-plates” polarizers [17].

3. Experimental Results

3.1 Materials and Setups

To construct the filters, Cloeren GOTDG002 cover glasses were used. The glasses were mounted onto a Thorlabs SFH3 filter holder. For transmission spectrum measurements two setups were used. A Perkin Elmer Lambda 950 UV-Vis-NIR spectrophotometer with a Si detector and an integrating sphere served for initial spectral measurements. This instrument has an incoherent light source (tungsten-halogen lamp) and measures total transmittance. For measurements of specular transmittance with a coherent light source a dedicated optical setup was used. A Fianium WhiteLase SC400 supercontinuum laser was utilized as a coherent and broadband light source. It emits 8 W of total light power in the form of a 3 mm diameter beam with 6 ps pulse duration in the 400-2400 nm spectral range. The light intensity is reduced using a pulse picker for most of the measurements to avoid causing damage to metal and semiconductor optical components. The light from the laser was split into two paths using a 50:50 beamsplitter. The transmitted part of light was analyzed with an AvaSpec-3648 fiber spectrometer, while the reflected part was measured with a Thorlabs S121C photodiode power sensor. The resolution of the measurement is approximately 0.3 nm with the supercontinuum laser setup and < 0.1 nm with the UV-Vis spectrometer. A Thorlabs S314C thermal power sensor was used for damage threshold tests.

3.2 Results and Discussion

The above described setups have been used to analyze filter properties upon a variety of testing conditions. The comparison between spectra obtained using the supercontinuum laser with fiber spectrometer and the UV-Vis spectrometer with halogen lamp is presented in Fig. 6 for a 10 glass slide filter. The complex refractive index of glass in the filters can be obtained by fitting experimental glass transmittance with transmittance of glass described by Cauchy model. The extracted Abbe number is 60 ± 5, while the refractive index at 589.3 nm is 1.52 ± 0.1.

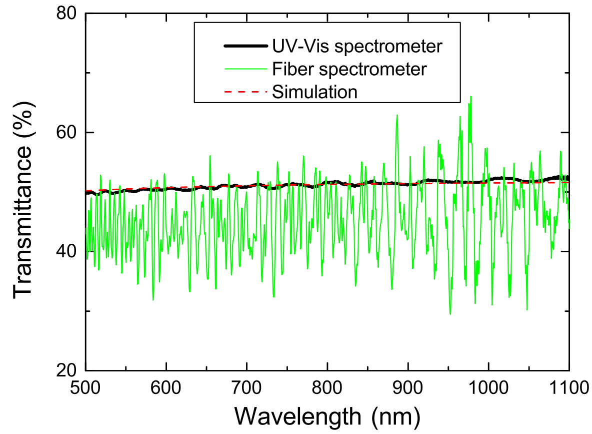

Fig. 6. Comparison of transmission spectra for a 10 glass slide filter obtained with different setups and transfer matrix method simulation.

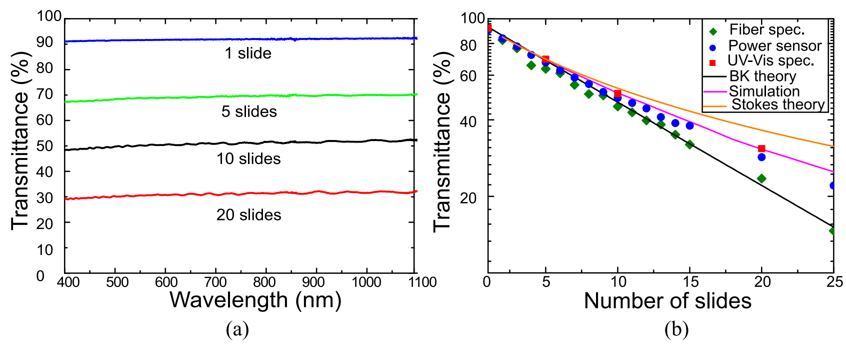

Fig. 7. Transmittance of ND filters with various numbers of glass slides: a) transmission spectra measured with UV-VIS spectrometer, b) typical transmittance obtained experimentally (symbols) compared with fully linearly averaged simulation (pink curve), Stokes (orange curve) and BK theory (black curve).

When measurements are taken with the UV-Vis spectrometer with incoherent light source, the resulting transmission spectrum contains a low amount of random fluctuations and the standard deviation of the spectrum results mostly from the dispersion of glass (see the black curve in Fig. 6). Consequently, it is possible to simulate the UV-Vis spectra for glass ND filters with the method described in Section 2.2 (see the red curve in Fig. 6) using extracted refractive index data. The relative standard deviation of the experimental transmittance spectrum is 2%. The increase in comparison with the simulated value (0.8%) can be attributed to fluctuations arising from interference effects. In contrast, measurements with the supercontinuum laser result in the observation of fine-scale fluctuations, despite of a similar spectral resolution (see the green curve in Fig. 6). We attribute this fact to coherent propagation within the stack.

The transmittance spectra of filters with varying number of slides measured with UV-Vis spectrometer are presented in Fig. 7(a). The standard deviation of the spectrum increases with increasing number of slides, due to increasing influence of dispersion on the filter properties, while the average transmittance decreases substantially with increasing number of slides. This dependence has been compared with numerical simulations in Fig. 7(b). The UV-Vis spectrometer result does neither follow the BK (5) nor Stokes (6) theory. However, transfer matrix simulations (pink solid line in Fig. 7(b)) with phase averaging correspond well to the experimental dependence between transmittance and number of glass slides.

A distinctly different behavior is observed when the supercontinuum laser is used to illuminate the filters. The typical transmittance value measured from 400 to 1100 nm wavelength with the fiber spectrometer deviates from fully linearly averaged simulation result. The dependence between

TABLE 2
Total Transmittance of 10 Glass Slides as a Function of Laser Repetition Rate

Power density (W/cm^2)	Laser rep. rate (MHz)	Total transmittance (%)
2.8	2	38.97
7	5	38.54
28	20	38.89
113	80	39.1

transmittance and number of slides is fitted much better with BK theory indicating that using a coherent light source results in increased degree of coherence of light propagating within the structure. This process leads to large spectrum deviations over a narrow range and increase in standard deviation (5.8% for 10 slides) meaning that for low power narrow-band coherent light sources, glass slides might not be an improvement in comparison with traditional ND filters.

Asides from the fiber spectrometer, a photodiode power sensor was used for measuring typical filter transmittance (see blue points in Fig. 7(b)). While the values obtained with the fiber spectrometer do not correspond to the simulation results, the results of glass ND filter transmittance measurements with the power sensor match the simulated dependence between transmittance and number of slides more accurately (we attribute the small deviation to scattering). This discrepancy between two measurements of the filters transmittance with the same light source results from the fact that the value measured with the power sensor does not take into account rapid fluctuations of the spectrum, since the measurement is not spectrally resolved.

The glass slides have been tested for their damage threshold under supercontinuum laser illumination by measuring the transmittance with the thermal power sensor for various power density values obtained by varying the pulse repetition rate. No visible damage or transmittance value change has been observed regardless of pulse repetition rate used, even for the average power density of 113 W/cm^2 corresponding to the repetition rate of 80 MHz. Thermal power sensor measurement data for a 10 glass slide stack is presented in Table 2.

3.3 Applicability to Solar Cell Testing

As a consequence of their high damage threshold, our neutral density filters can be used to control light intensity of high power incoherent light sources. With emergence of concentrator photovoltaics, the capability to reproduce solar spectra at various light power became essential for credible device testing. Bearing that in mind, we used the filters in a commercial concentrated sun simulator. The solar simulator contains a 1000 W xenon lamp, a microlens array for illumination homogenization and a Fresnel lens for focusing. The AM1.5 filter shapes the spectrum to achieve AAA solar simulator class. In order to evaluate applicability of the glass ND filter in solar cell testing, we measured the short-circuit current as a function of light intensity modified by various glass ND filters. The short-circuit (I_{sc}) current depends linearly on light power provided the spectrum is intensity independent and the solar cell is not damaged by light power [18]. For our tests we used 2×2 mm^2 CIGSe solar cells with 9 % efficiency and I_{sc} of 0.253 mA measured under a reference solar simulator.

The number of slides has been adjusted so that we could obtain intensities from 12 to 100 suns (measured with the thermal power sensor). The obtained relation between light intensity and total number of slides is different from that for the supercontinuum laser. This stems from the angular dependence of the filters' transmittance. The xenon lamp emits light in broad range of angles. Still, it is possible to obtain 12% transmittance with a reasonable amount of glass plates (see Fig. 8(a)). Further transmittance decrease (down to 1 sun) is achieved by removing the focusing lens from the light path.

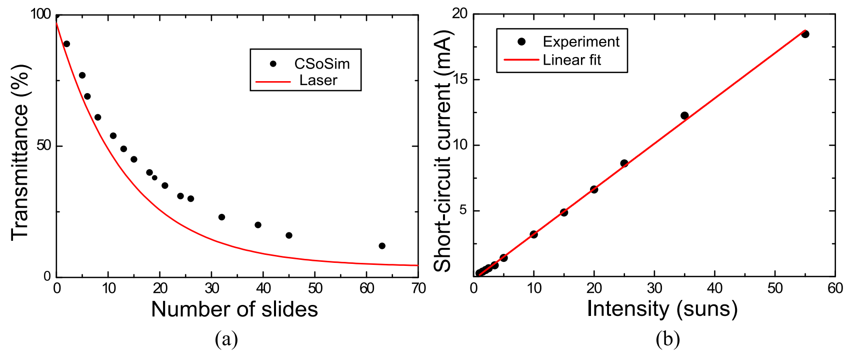

Fig. 8. Experimental results with the concentrated sun simulator (CSoSim): a) filter transmittance as a function of number of slides measured under sun simulator illumination (dots) compared with transmittance under supercontinuum laser illumination (line), b) short-circuit current as a function of light intensity.

The short-circuit current at 1 sun intensity measured with concentrated sun simulator is 0.249 mA, which agrees with the reference measurement. We have observed linear increase in I_{sc} with increasing light intensity, which leads to the conclusion that the glasses have sufficiently flat transmission spectrum to enable reliable solar testing. No visible damage or undesired change in filter transmittance has been observed while performing these experiments further proving extraordinarily high damage threshold in comparison with other ND filters.

4. Conclusion

We have presented that a stack of glass slides can be utilized as a ND filter in the visible and near infrared (400-1100 nm wavelength). The transmittance is reduced in comparison with a single glass slide as a result of increased number of interfaces and interference of multiply reflected waves. The filter spectrum is shaped by material dispersion and interference patterns. We have observed that in our glass ND filters fine-scale fluctuations are suppressed when an incoherent light source is used leading to broadband flat transmission spectra.

Angular distribution of light influences the filter transmittance. We have presented the numerically calculated dependence between average transmittance and AOI. This opens a route to further decrease the ND filters' transmittance for collimated light sources or predict its value for uncollimated light sources.

The damage threshold of glass ND filters is larger than previously known ND filters, which provides control over intensity of high power light sources. The transmittance of the filter varies with the number of slides. These properties make our filters suitable for applications in concentrated sun simulators. We have shown that intensity reduction by a factor of 10 can be achieved for solar cell testing without damaging the filters or observing nonlinear short-circuit current dependence on intensity.

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