Resonance-Induced Dispersion Tuning for Tailoring Nonsolitonic Radiation via Nanofilms in Exposed Core Fibers

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Efficient supercontinuum generation demands for fine-tuning of the dispersion of the underlying waveguide. Resonances introduced into waveguide systems can substantially improve nonlinear dynamics in ultrafast supercontinuum generation via modal hybridization and formation of avoided crossings. Using the example of exposed core fibers functionalized by nanofilms with sub-nanometer precision both zero-dispersion and dispersive wave emission wavelengths are shifted by 227 and 300 nm, respectively, at tuning slopes higher than 20 nm/nm. The presented concept relies on dispersion management via induced resonances and can be straightforwardly extended to other deposition techniques and film geometries such as multilayers or 2D materials. It allows for the creation of unique dispersion landscapes, thus tailoring nonlinear dynamics and emission wavelengths and for making otherwise unsuitable waveguides relevant for ultrafast nonlinear photonics.

1. Introduction

Spectral broadening using supercontinuum generation (SCG) relies on nonlinear material responses at high light intensities. Such intensities are realized in fiber optics via ultrashort optical pulses and strongly confining geometries, having led to applications such as nonlinear light generation,[1,2] spectroscopy,[3] nonlinear pulse compression,[4] and optical switching.[5] The key to efficient SCG is precise management of modal dispersion. Within soliton-based SCG, dispersion engineering enables controlling both the fission of higher-order solitons into their fundamental counterparts as well as the associated emission of excess energy to phase-matched dispersive waves (DWs).[6,7] Some dispersion management approaches involve incorporating untraditional materials (e.g., using birefringence), tailoring waveguide geometry or employing sophisticated microstructured claddings.[8–12] However, reaching specific dispersion values at prominent laser wavelengths remains challenging due to insufficient knowledge on material properties and inherent fabrication inaccuracies.[13–15] Approaches involving exchangeable core materials (liquids or gases[7,16–18]) or post-fabrication tuning schemes (via, e.g., temperature,[19,20] pressure,[21,22] or mode excitation[23]) are being employed, while having solid glass fibers is favorable for many applications.

A novel dispersion management approach giving access to previously unknown dispersion landscapes relies on including geometry-mediated resonances. As shown for gas-filled antiresonant hollow core fibers, the coupling of the central core mode to strand resonances yields a dispersion landscape with unprecedented properties.[1,22,24,25] Pumping such a system close to the zero dispersion wavelength that is induced by a spectral resonance yields octave-spanning supercontinua with bandwidths that massively exceed those of corresponding resonance-free fibers. These results clearly suggest that employing resonances for dispersion management is a general concept being particularly useful for ultrafast SCG.

One approach to include resonances into waveguides conceptually employs dielectric nanofilms located on the fiber core (see Figure 1). Films with nanometer thickness are highly relevant within current photonics, examples of which include hybrid plasmonic mode couplers[26,27] or fiber refractive index (RI) sensors.[28] Nanofilm functionalized fibers have also been

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recently employed for third harmonic generation in exposed core fibers (ECFs).\[29,30\]

In this work we show that dielectric nanofilms deposited on the core of ECFs allow for the unprecedented engineering of modal dispersion, enabling SCG in a fiber geometry that without film provides no significant spectral broadening. Specifically, employing nanofilms made from titanium dioxide (TiO\textsubscript{2}) of thicknesses often so thin nanometers allow shifting both zero-dispersion wavelength (ZDW) as well as spectral location of DW. Our study includes simulations of the impact of the TiO\textsubscript{2} nanofilm on modal properties and an experimental verification of the dispersion tuning concept, showing that changing the TiO\textsubscript{2} film thickness by 10 nm imposes the DW to shift by 300 nm.

2. Concept

The SCG mechanism relevant in this work relies on the fission of higher-order optical solitons into their fundamental counterparts. This process is associated with the emission of excess energy to a DW and a continuous spectral red-shift resulting from the Raman response of the core material (silica in the present case).\[31,32\] Within the scope of ultrafast soliton-based SCG, the central laser pulse wavelength $\lambda_p$ is required to be within the anomalous dispersion (AD) domain close to the wavelength of vanishing dispersion, i.e., to the ZDW $\lambda_{ZD}$. The latter parameter is a key design figure for optimizing waveguides within the scope of soliton-based SCG. The spectral locations of fundamental solitons and DWs ($\omega_0$ and $\omega_f$) are correlated via a phase-matching condition that is mainly determined by the dispersion of the waveguide used:\[31\]

$$\beta(\omega_f) - \frac{\alpha_f}{\nu_f} = \beta(\omega_0) - \frac{\alpha_0}{\nu_0} + 0.5\gamma P_s \quad (1)$$

with the propagation constant of the fundamental mode $\beta$, the group velocity at the soliton frequency $\nu_s$, the nonlinear parameter $\gamma$ and the peak power of the soliton $P_s$. Equation (1) reveals that in particular the waveguide dispersion has significant impact on the spectral location of the DW, i.e., on the generated spectra.

3. Operational Principle

The overall idea of resonance-imposed dispersion tuning relies on the inclusion of an additional resonance into the waveguides system, imposing modal hybridization and thus modifying the waveguide dispersion. Within the context of this work, a resonance is included via an additional mode supported by a high RI nanofilm located on one side of the waveguide. To qualitatively reveal the impact of modal hybridization, a slab waveguide geometry resembling experimental circumstances is simulated (RI distribution represented by the bars on the right of Figure 2c,d).\[34\] Specifically, we assume an infinitely extended silica core layer (thickness $d = 1.7 \mu m$) embedded in air and covered by a TiO\textsubscript{2} nanofilm (thickness $t = 40$ nm). In absence of the nanofilm, both effective index $n_{ef}$ and group velocity dispersion $\beta_2$ of the fundamental mode (TE-polarization) reduce monotonically for increasing wavelength (blue dashed lines in Figure 2a,b) with $\lambda_{ZD} = 920$ nm. The situation fundamentally changes in case the nanofilm is included: Here, the high-RI mode which represents the resonance is initially located mainly inside the nanofilm at short wavelengths, anti-crosses with the glass core mode at around $\lambda = 800$ nm and gradually transforms into a fundamental mode (Figure 2c). The low-RI mode that is the fundamental core mode at short wavelengths, anti-crosses with the glass core mode at around $\lambda = 800$ nm and gradually transforms into a fundamental mode with increasing wavelength where most modal power is located inside the silica core (Figure 2c). The low-RI mode that is the fundamental core mode at short wavelengths, anti-crosses with the glass core mode at around $\lambda = 800$ nm and gradually transforms into a fundamental mode with increasing wavelength where most modal power is located inside the silica core (Figure 2c). The low-RI mode that is the fundamental core mode at short wavelengths, anti-crosses with the glass core mode at around $\lambda = 800$ nm and gradually transforms into a fundamental mode with increasing wavelength where most modal power is located inside the silica core (Figure 2c).
shifts the ZDW by more than 300 nm close to the telecommuni-
cation regime, making this waveguide to fulfill the prerequi-
sites for soliton-based SCG (pump wavelength close to ZDW).
The observed wavelength-dependent behavior is a result of an ad-
ditional resonance introduced into the waveguide system and is
not present in case a nanofilm with a RI lower than that of silica
is used. It is interesting to note that the cut off wavelength of
the isolated high-RI mode (dotted red line in Figure 2a) is located
in close proximity of the anti-crossing.

4. Fiber Geometry Used Here

To demonstrate the nanofilm induced dispersion tuning concept
in the experiment, we consider a small-core ECF made from silica
as waveguide platform. This sophisticated microstructured fiber
consists of three air holes surrounding a suspended core with
one open hole making it side-wise accessible to the environment
(Figure 1a–c). This fiber design, developed by S. Warren-Smith
et al.[34] and used in an alternative version by Yang et al.[35]
opens the possibility of employing conventional layer deposition
techniques such as evaporation and sputtering, although not being
suitable for soliton-based SCG (pump wavelength close to ZDW).
The observed wavelength-dependent behavior is a result of an ad-
ditional resonance introduced into the waveguide system and is
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5. Simulations

Finite Element modeling (COMSOL Multiphysics) has been used to
calculate field profiles and modal dispersion of the fundamental
mode for various configurations. To accurately resemble the
experimental situation, the real fiber geometry was taken from
the scanning electron microscope (SEM) image of the core sec-
tion (shown in Figure 1c) and imported into the software. In addi-
tion to the in-house measured dispersion of the TiO₂ nanofilms
using ellipsometry and a test sample (for more details on the
nanofilm see the Supporting Information), the material disper-
sion of silica reported by Malitson[37] was used. Group velocity
were calculated from numerically differentiating the spectral
distribution of \( n_{eff} \) (step size \( \Delta \lambda = 10 \) nm). Note that both
simulations and experiments show that tailored SCG is achieved
only for the horizontally polarized mode (parallel to the nanofilm,
directions visualized in Figure 1c), which is solely considered in
the following.

Numerical simulations of the nanofilm functionalized ECF
geometry show a similar modal behavior as observed for the
slab waveguide model (Figure 2a), including modal hybridiza-
tion, anti-crossing and dispersion modification (inset of Fig-
ure 3a). Note that since the emission wavelength of the ultra-
fast laser used here is located at telecommunication wave-
length, the subsequent discussion is entirely focused on the
spectral interval on the long wavelength side of the reso-
rance, allowing us to restrict the discussion to the high-RI
mode.

The strong wavelength dependence of the dispersion modifi-
cation is particularly visible by the fraction of power inside the
nanofilm defined as \( f = \frac{\int_{\lambda_{lower}} S_z \, d\lambda}{\int_{\lambda_{lower}} S \, d\lambda} \) with the longitudi-
dinal Poynting vector \( S_z \). As shown in Figure 3f is significantly

Figure 2. Impact of a waveguide-based resonance on the dispersion and field properties of a nanofilm (thickness \( t = 40 \) nm) enhanced slab waveguide (TE-polarization). Spectral distributions of (a) relative effective index \( \Delta n_{eff} = n_{eff} - n_{SiO₂} \) and (b) group velocity dispersion. Solid lines are the hybridized modes (magenta: high-RI mode, light cyan: low-RI mode), dashed and dotted lines are the corresponding curves for the modes of the isolated waveguides (dashed, blue: air/silica/air, dotted, red: silica/TiO₂/air). The red square represents the cut-off wavelength of the isolated high-RI mode (868 nm) while the colored backgrounds in (b) indicate the two dispersion regions (light red: normal dispersion (ND), light green: anomalous dispersion (AD)) with a color scale ranging linearly from zero (black) to unity (white). Colored bars on the right of the plots show the RI distribution of the slab waveguide geometry (gray: air, light blue: silica, green: TiO₂-nanofilm). The vertical dashed lines are the ZDWs highlighted by the dots in (b).
The nonlinear dynamics of the investigated configuration have been simulated by solving the Generalized Nonlinear Schrödinger Equation (GNLSE) considering random phase noise.\[38\] The simulations include the full modal dispersion obtained via finite element modeling and self-steepening to account for the dispersion of $\gamma$. A sech²-shaped pulse with a temporal width of 20 fs (FWHM $\approx$35 fs, peak power 9 kW and central wavelength 1570 nm) is assumed resembling experimental conditions. Noise is included via the one-photon-per-mode model\[6\] and each presented spectrum is the ensemble average of 30 individual simulations.
For nanofilms with \( t < 46 \text{ nm} \) (Figure 5a), no spectral broadening can be observed, although the spectra are slightly red-shifted due to Raman scattering (\( \lambda = 1.6 \mu \text{m} \)). For \( t > 46 \text{ nm} \), clear DW formation emerging at \( \lambda = 1.045 \mu \text{m} \) can be observed that moves toward longer wavelengths at a tuning slope of \( S_{DW,\text{sim}} \approx 30 \text{ nm/nm} \) until \( \lambda_0 \) reaches the ND domain (spectral evolution and phase matching curves shown in the Supporting Information). As the soliton number (Figure 5b) is small \((N < 2)\) for the majority of nanofilm thicknesses single soliton propagation without fission is observed in the experimentally realized configurations. The small soliton number is also the reason for the single and ensemble spectra being almost identical, showing the negligible impact of phase noise, which is primarily a result of using ultrashort pulses and low peak powers.

6. Experimental Supercontinuum Tuning

The nonlinear experiments rely on a combination of an ultrashort fiber laser operating at telecommunication wavelengths (FemtoFiber pro IRS II, repetition rate 80 MHz, Toptica Photonics), high-precision fiber launching stages, polarization control and an optical spectrum analyzer (OSA, Ando AQ6317), more details about the setup can be found in the experimental section. The automatic optimization of the compressor is disabled to allow for manually tailoring the initial laser chirp to achieve the shortest pulse duration and the highest peak power inside the ECF, estimated to be 30 fs and 12.5 kW (at 190 mW average laser power), respectively. No laser induced damage was observed at any time of the experiments. A reference fiber without nanofilm and fibers with very thin TiO2 coatings \((t \leq 37.5 \text{ nm})\) show only very weak spectral broadening solely due to self-phase modulation. Samples with \( t \geq 42.5 \text{ nm} \) show clear evidence for soliton and DW formation as a result of \( \lambda_{\text{sol}} \) shifting toward the pump. The spectra of samples with thicknesses 42.5, 47.5, and 52.5 nm are presented in Figure 6 and show DWs at 1050, 1160, and 1350 nm at maximum average input power of \( \approx 190 \text{ mW} \), respectively. At the long wavelength side of the pump formation of a soliton can be observed at roughly 1650 nm for all three cases. Note that the blue-shift of the DW for increasing average power is overall a result of the corresponding red-shift of the soliton in accordance with Equation (1). No relevant spectral features were observed for \( \lambda > 1.75 \mu \text{m} \), which was examined by a mid-IR OSA (Ando AQ6375) up to 2.4 \mu m. For nanofilms with \( t > 58 \text{ nm} \) the pump wavelength enters the normal dispersion regime and no spectral broadening can be measured.

Uncoated ECFs show coupling efficiencies <20%, resulting from the small core size. Although TiO2 is transparent, adding the nanofilm increases the losses as observed by Purniawan et al.\( ^{[39]} \) which is presumably caused by an additional scattering (Table 1). Note that during the TiO2 deposition water accidentally entered parts of the ECFs, with traces remaining in the final samples (decomposition of an unsuitable sealing grease).

For the sample with \( t = 42.5 \text{ nm} \), cutting away a strong scattering center (i.e., decreasing fiber length from 6.8 to 5.1 cm) increased the transmittance by one order of magnitude from 0.7% to 7.4%, revealing the potential of increasing the transmittance of coated ECFs by optimizing the deposition process. Note that the spectra shown in Figure 6 were recorded before the scattering center was cut away.

Measured mode profiles for the ECF with \( t = 52.5 \text{ nm} \) at the spectral locations of DW, pump and soliton wavelength using bandpass filters are presented on the top of Figure 6 verifying fundamental mode propagation at all wavelengths. Due to the large pixel size (30 \mu m) of the IR camera (IK1513, ABS GmbH Jena) and aberrations at large magnifications the triangular mode shape is not visible. An analyzer confirms that the mode has horizontal polarization as used in simulations. Experiments in the perpendicular polarization yield up to three times more transmission for coated samples at the expense of no measurable SCG, because the relevant ZDW is located at >200 nm shorter wavelength compared to the horizontal case for all layer thicknesses considered. Note that the vertically polarized fundamental core mode anti-crosses with the second-order horizontally polarized nanofilm mode which has a much shorter cut-off wavelength compared to the first-order layer mode being used in the horizontal situation. Moreover, the impact of material losses is smaller for the vertical case since the fraction of electric field inside the nanofilm is reduced (0.2% compared to 1.8% in the horizontal case for \( t = 45 \text{ nm} \) at \( \lambda = 1600 \text{ nm} \)).

A direct comparison of the nanofilm thickness dependence of the spectral locations of the various features obtained from experiments and simulations is shown in Figure 7. A pronounced increase of the DW wavelength \( \lambda_{\text{DW}} \) (DW tuning slope \( S_{DW,\text{exp}} \approx \Delta \lambda_{\text{DW}} / \Delta t \approx 29.8 \text{ nm/nm} \), red dashed line in Figure 7) for thicker films is observed, while the wavelength of the soliton \( \lambda_{\text{sol}} \) remains nearly constant. This behavior of the DW is therefore solely due to the modification of the waveguide dispersion by the high RI nanofilm, with the tuning slope matching calculation using Equation (1) and nonlinear pulse propagation simulations \((S_{DW,\text{sim}} \approx 29.2 \text{ nm/nm} \) and \( S_{DW,\text{sim}} \approx 30 \text{ nm/nm} \). Orange dotted and pink solid lines in Figure 7). The former takes into account the experimentally measured soliton wavelengths: \( \lambda_{\text{sol}} = 1650 \text{ nm} \) for \( t = 52.5 \text{ nm} \), \( \lambda_{\text{sol}} = 1664 \text{ nm} \) for \( t = 47.5 \text{ nm} \).
Figure 6. Experimental confirmation of the concept. Measured supercontinuum spectra for nanofilm functionalized exposed core fibers with TiO2 thickness of a) 42.5, b) 47.5, and c) 52.5 nm for different average incoupling powers (horizontal polarization). The top row shows measured mode profiles for DW, pump, and soliton exemplarily for the fiber coated with a 52.5 nm thick film (numbers in the images indicate the center filter wavelength).

Table 1. Key linear and nonlinear parameters for the set of nanofilm functionalized ECFs investigated here.

| Layer thickness | $\gamma$ at $\omega_s$ [W$^{-1}$ m$^{-1}$] | Transversality | Transmittance | Soliton number | Fiber length | $\lambda_D$ [mm] | $\lambda_{sol}$ [nm] | ZDW [nm] | DW [nm] |
|-----------------|--------------------------------------|----------------|---------------|----------------|--------------|----------------|------------------|---------|---------|
| 0 nm            | 0.036                                | 0.96           | 18.6%         | 0.90           | 6.8 cm       | 2.0            | 2.4              | 771     |         |
| 42.5 nm         | 0.039                                | 0.97           | 0.7%          | 1.09           | 6.8 cm       | 2.6            | 2.2              | 1250    | 1050    |
| 47.5 nm         | 0.042                                | 0.97           | 3.7%          | 1.28           | 3.7 cm       | 3.4            | 2.1              | 1364    | 1171    |
| 52.5 nm         | 0.046                                | 0.97           | 1.9%          | 1.73           | 5.2 cm       | 5.6            | 1.9              | 1477    | 1348    |

Figure 7. Comparison of the thickness dependence of the various spectral features measured and simulated. Green: measured soliton wavelength. Blue: Zero-dispersion wavelength, separating the anomalous (light green) and normal (red) dispersion domain. Pink: wavelength of DW obtained from the nonlinear pulse propagation simulations shown in Figure 5. Red dots: measured spectral locations of the dispersive wave. Orange dots: calculated corresponding DW wavelengths using Equation (1) assuming the experimentally measured soliton wavelengths. The dashed lines are linear fits to the data points. Note that the pink line start at $t = 46$ nm as the nonlinear simulations suggest no DW for thinner nanofilms.

$\lambda_{sol} \approx 1630$ nm for $t = 42.2$ nm while the nonlinear simulations include the phase matching condition with the soliton wavelength at the DW onset distance. Alternatively, $\lambda_{DW}$ could be calculated using the GVD and third order dispersion at the soliton wavelength only.\(^{[40]}\) Albeit a good approximation for specific situations, we found that this method is not applicable in our case because the fiber dispersion is highly influenced by the modal anti-crossing which cannot be approximated by a Taylor expansion up to third order.

In comparison to the measured wavelength (red dots in Figure 7), the calculated $\lambda_{DW}$ are shifted to values that correspond to 4–5 nm thicker nanofilms. This difference we attribute mainly to the following experimental uncertainties: The largest contributions is imposed by the ellipsometry characterization of the TiO2 layer (Figure S1, Supporting Information), as measured layer thicknesses have an accuracy of $\pm 1$ nm and the RI may vary up to $\pm 0.05$. A test calculation assuming a constant RI of TiO2 ($n_{TiO2} = 2.3$) shows that this variation has the same effect as a thickness modification of 1.5 nm with the original TiO2 dispersion. Additionally, the dimensions of the fiber determined by SEM could be too large and might vary along its length. Decreasing the SEM scale bar by 5% corresponds to another thickness variation of 0.4 nm. A further contribution of effective 0.5 nm results from the simulated layer thickness being in vertical direction only (see orientation in Figure 1) instead of normal to the curved surface.

Table 1 summarizes the most important parameters for classifying the nanofilm functionalized ECF within the context of nonlinear waveguides (parameters defined by Agrawal\(^{[22]}\)). The determination of the nonlinear coefficient $\gamma$ relies on integrating $S_z$ in the respective materials and includes the contribution of the nanofilm (nonlinear RI of TiO2 and silica: $n_2,TiO2 = 9 \times 10^{-19}$ m$^2$ W$^{-1}$\(^{[41]}\) (average of both crystal axis values of bulk rutile TiO2 at 800 nm) and $n_2,silica,1550nm = 2.8 \times 10^{-20}$ m$^2$ W$^{-1}$\(^{[42]}\)). Note that since the transversality of the fundamental mode is close to unity, a full vectorial model ansatz for the calculation
of γ is not required in accordance with the argumentation by Afshar et al.\textsuperscript{[43]}

It is important to mention that the soliton numbers given in Table 1 are close to unity and therefore no soliton fission is occurring at the power levels used here. The peak on the long wavelength side of λ\textsubscript{c} (Figure 6) is in fact the initially excited fundamental soliton that red-shifts due to the Raman effect and continuously transfers excess energy to the DW in case of phase matching. The reduced energy transfer efficiency between DW and soliton for the situation of \( t = 42.5\, \text{nm} \) is in compliance with increasing soliton number and third order dispersion as well as decreasing GVD at the soliton wavelength for thicker layers.\textsuperscript{[40,44]}

Despite a marginal enhancement of the nonlinearity for thicker layers, the main reason for the increasing soliton number is the reduction of the GVD at λ\textsubscript{c}, represented in a longer dispersive length L\textsubscript{D}. Overall changing the nanofilm thickness shifts the ZDW which affects the magnitude of the GVD, making resonance induced dispersion tuning the major contributor to the effects observed.

7. Discussion

The SCG tuning concept represents a tuning approach that can principally be applied to any waveguide structure with a free standing core, for instance including planar ridge waveguides\textsuperscript{[45]} or fiber optical tapers.\textsuperscript{[26]} The achieved DW tuning bandwidth of 298 nm exceeds those of other post-fabrication tuning scheme for a fixed pump wavelength in the near infrared employing changing either temperature or pressure \( (140\textsuperscript{[19]} \text{ and } 60\text{nm}, \textsuperscript{[22]} \text{ respectively}) \). To improve bandwidth and uniformity of the generated spectra further coupling efficiencies have to be increased or the laser needs to be replaced in order to obtain higher in-fiber peak power and thus to excite higher order solitons and enable soliton fission. One simulated representative configuration that yields larger spectral bandwidth via the use of longer pulses showing the potential of the approach regarding supercontinuum generation is described in simulations shown in the Supporting Information (Figure S2 (Supporting Information) and text related). Another promising configuration for obtaining a more uniform electromagnetic energy distribution at the low laser powers used here includes a sequence of short sections of nanofilms with successively increasing nanofilm thickness within a single fiber. Details of the simulation results can be found in the Supporting Information (Figure S3 (Supporting Information) and related text).

A substantial increase of the RI sensitivity can be anticipated in case nanofilms with higher RIs are considered. To qualitatively demonstrate this effect, the cut-off wavelength \( \lambda_{\text{cut}} \) of the fundamental mode of the TiO\textsubscript{2} nanofilm sandwiched between silica and air within the used slab waveguide model (dotted red line in Figure 2a), serving as a rough indicator for the location of the anti-crossing is investigated (details of the calculations can be found in the Supporting Information). Neglecting material dispersion \( (n_{\text{silica}} = 1.45) \) shows that the cut-off tuning slope \( m_{\text{cut}} = d\lambda_{\text{cut}}/dt \) (Figure 8, green curve) increases by more than a factor of two compared to the TiO\textsubscript{2}-films considered here in case RI \( \approx 3 \) films are used. Here, assuming a nanofilm thickness of \( t = 40\, \text{nm} \) allows \( \lambda_{\text{cut}} \) to reach telecommunication wavelength (Figure 8, purple curve). These results suggest a substantial increase of the RI sensitivity in case chalcogenide (RI \( \approx 2.4 \)) or semiconductor (RI \( \approx 3 \)) nanofilms are considered.

Other aspects of future investigation involve the optimization of the nanofilm properties with the overall aim to reduce modal attenuation and nanofilms that have properties that can be modified externally.

8. Conclusion

Supercontinuum generation represents a highly important scheme for the generation of light with tailored properties and demands precise fine-tuning of the dispersion of the underlying waveguide. Here we show that resonances introduced into waveguide systems can substantially improve the nonlinear dynamics in the ultrafast supercontinuum generation process via a unique dispersion landscape. Specifically, high refractive index nanofilms located on the top of exposed waveguide cores induce modal hybridization and formation of anti-crossings, resulting in a strong modification of the waveguide dispersion and in particular of the group velocity dispersion. In addition to simulations and a slab waveguide model, the feasibility of the concept was experimentally demonstrated on the example of an exposed core fiber that includes a high refractive index nanofilm on the accessible side of the core. Sub-nanometer thickness control of TiO\textsubscript{2} nanofilms is provided via atomic layer deposition allowing for unique manipulation of the dispersion. We show that nanofilms with thicknesses of about 40 to 55 nm allow for spectrally shifting the zero-dispersion wavelengths close to the pump wavelength, enabling efficient energy transfer from a fundamental soliton to a dispersive wave. Increasing the nanofilm thickness from initially 42.5 to 52.5 nm shifts the dispersive wave from 1050 to 1348 nm at a record high tuning slope of 30 nm/nm as confirmed by simulations and experiments.

The presented concept provides several key advantages such as the generation of broadband light with waveguides that are otherwise unsuitable for supercontinuum generation or the tuning of emission wavelengths to specific spectral domains. Our
concept is straightforwardly compatible with other state of the art deposition technologies and leaves significant room for further improvements and research, since sophisticated film-type structures such as multilayers or highly nonlinear 2D-materials\cite{46} might be employed.

9. Experimental Section

The experimental setup for the nonlinear experiments used in this work is shown in Figure 9. Attenuation of the input laser power is provided by rotating a \( \lambda/2 \)-plate in front of a fixed polarizer to minimize beam deflection, while a second \( \lambda/2 \)-waveplate enables polarization control. The incoupling to the exposed core fiber is realized by a single aspheric lens \( (C230TMD-C, \text{ Thorlabs Inc.}) \) to keep the amount of dispersive material in the light path before the waveguide as short as possible. A large core multimode fiber of 1 mm diameter is used to collect most of the broad spectrum in spite of chromatic aberrations of the outcoupling objective. Remaining aberrations cause the spectra (Figure 6) to exhibit an error of about –10 dB/500 nm, while here we optimized for the DW. Different coupling conditions and compressor prism positions for each fiber sample result in slightly changed spectra at low power because those parameters remain untouched as the power is reduced.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

anti-crossing, dispersive waves, nanolayer, optical fibers, solitons, TiO\textsubscript{2}

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