Supplementary Information for

3D-printed miniature spectrometer for the visible range with a 100 x 100 µm² footprint

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1. Miniature spectrometers overview

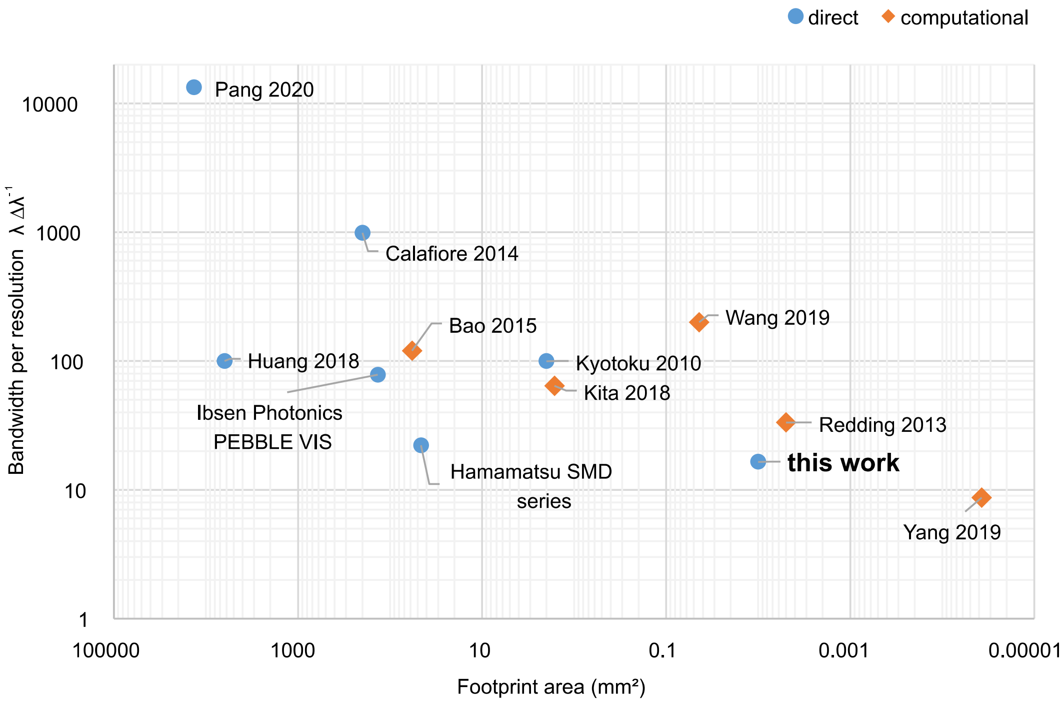

Figure S1 Bandwidth per resolution versus footprint area. The spectrometer presented in this work explores a novel size range for direct spectrometers (blue circles). Orange diamonds indicate computational spectrometers. All data points are labeled with first author and year or manufacturer and model, respectively: Bao 2015[1], Calafiore 2014[2], Hamamatsu SMD series[3], Huang 2018[4], Ibsen Photonics PEBBLE VIS[5], Kita 2018[6], Kyotoku 2010[7], Redding 2013[8], Pang 2020[9], Wang 2019[10], Yang 2019[11].

Bao 2015[1] states 2-3 nm general resolution (2.5 nm assumed in the graph), 0.5 mm filter spacing, and 196 filters in total on a 8.5 mm x 6.8 mm chip (chip size assumed in the graph). Hamamatsu SMD series[3] is specified with a volume of 11.5 mm x 4 mm x 3.1 mm. Due to its orientation, 11.5 mm x 4 mm are assumed in the graph as footprint area. Huang 2018[4] states a not further specified resolution better than 10 nm; therefore 10 nm are assumed in this graph. Ibsen Photonics PEBBLE VIS[5] is specified with a volume of 17 mm x 8 mm x 15 mm. Due to its orientation 17 mm x 8 mm are assumed in the graph as footprint area. Kita 2018[6] states 64 channels which are assumed as bandwidth per resolution ratio. The footprint area is not explicitly stated but has been extracted from their Figure 1c and determined to be 585 µm x 2.79 mm. Kyotoku 2010[7] states a not further specified footprint area less than 2 mm²; 2 mm² are assumed in the graph. Redding 2013[8] indicates the footprint area in Figure 1a as 50 µm x 100 µm which is assumed in the graph. Pang 2020[9] specifies the prototype size as 15 cm x 9 cm x 5 cm. 15 cm x 9 cm are assumed as footprint area. Yang 2019[11] states the size of the single nanowire as 0.5 µm x 75 µm which is assumed as footprint area in this graph. The voltage taps are not considered in this footprint area which is thus likely underestimated. A resolution of 15 nm is assumed as stated in the main text.

2. Spectral distribution of the monochromator

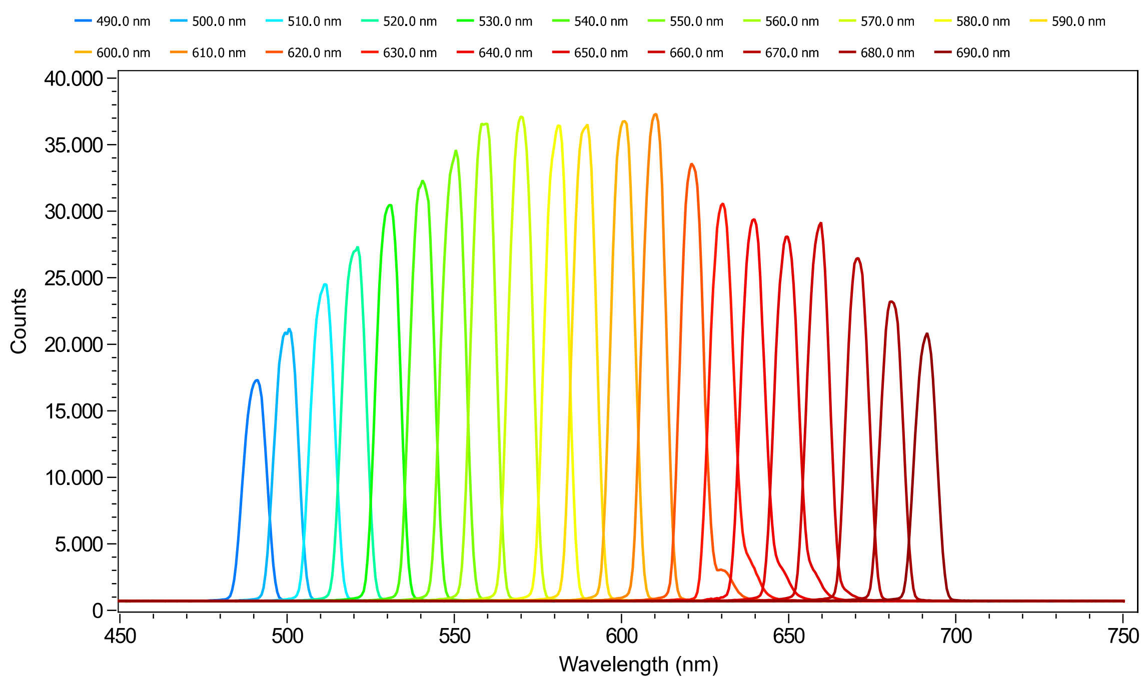

Figure S2 Spectral distribution of the monochromator used in the measurement setup for the given wavelengths. The monochromator is illuminated with a white light halogen lamp and the wavelengths are selected with a multimode fiber with 300 µm diameter (detailed description in the materials and methods section).

Figure S2 indicates the spectral distribution of the monochromator used in the measurements of the slit width and the spatial-spectral response of the 3D-printed spectrometer. The spectra were taken with an AvaSpec-ULS2048-RS-USB2 spectrometer. The linewidth is of the same magnitude as the resolution of the spectrometer under test, therefore, the measured linewidths of the microspectrometer are substantially widened. Consequently, the quantitative linewidth evaluation is determined from the laser measurements. **Figure S2** shows that the halogen lamp used as illumination source of the monochromator has a decrease in intensity towards both ends of the spectrum which leads to a reduced signal-to-noise ratio. Please note, that the intensity of the halogen lamp shifts towards the red with increasing supply voltage (wavelengths of the monochromator remain constant). Regarding the spatial-spectral response measurements the intensity distribution only affects the noise level since each profile is normalized to its own maximum.

3. Characterization of the chirped grating

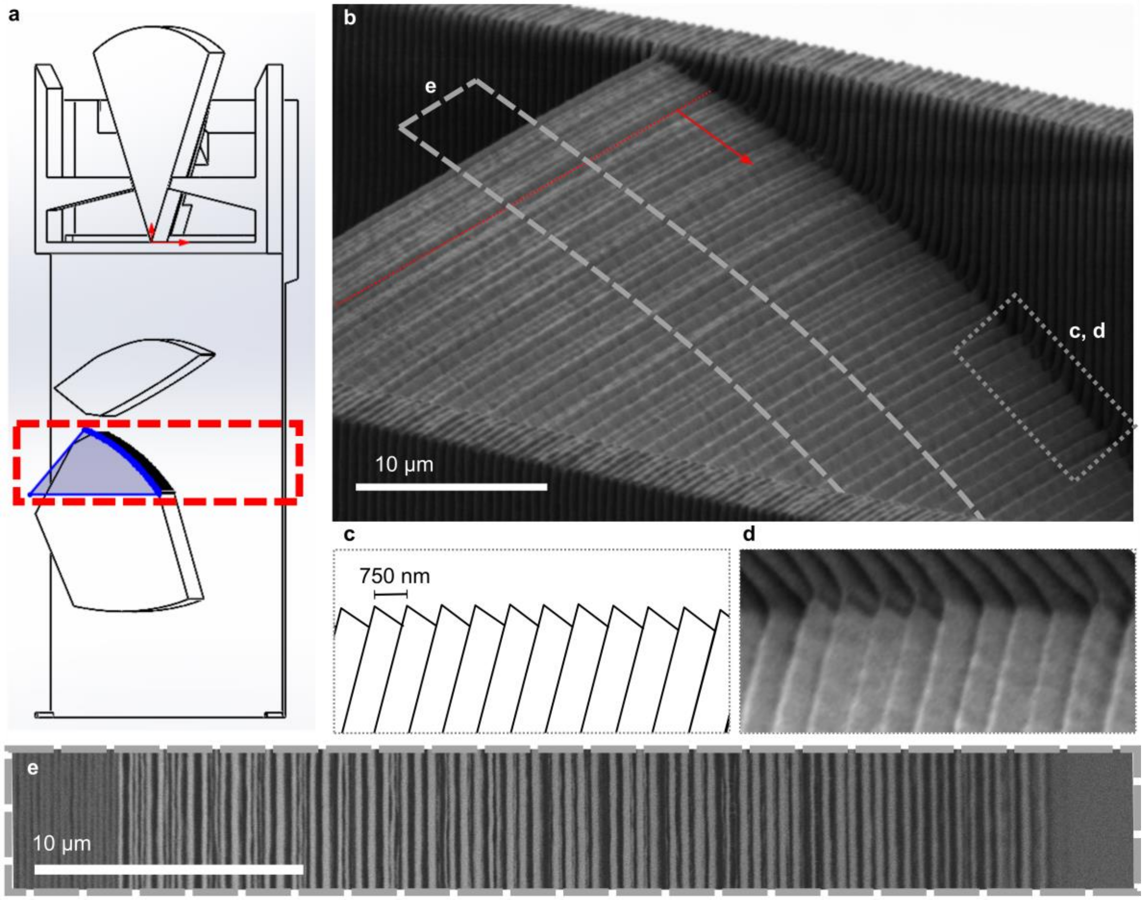

Figure S3 Scanning electron microscope (SEM) images of the chirped grating. **a** Cut view of the 3D-printed volume model. The red box indicates the excerpt of the model that has been printed for these measurements. The blue sketch indicates the extent of the grating surface that has been fabricated. **b** SEM measurement from a tilted side view. The red dotted line indicates the first grating line that was used in the complete spectrometer. **c** and **d** theoretical and measured triangular grating topography from the excerpt indicated in **b**. Brightness and contrast of the SEM measurement excerpt have been adjusted. **e** SEM measurement of the grating from a top view.

In **Figure S3** characterization measurements of the chirped grating are presented. In order to access the grating surface in the measurements, only the part of the complete spectrometer indicated in red in subfigure **a** was printed directly onto a glass substrate. The grating surface was extended towards higher frequencies (upper part) as indicated in blue. Scanning electron microscope (SEM) measurements were performed to characterize the grating lines and topography. The tilted side view shown in subfigures **b**, **c**, and **d** visualizes the triangular shape of the blazed grating line topography. The dotted red line and arrow in subfigure **b** indicates the first grating line that is used in the complete spectrometer. From the SEM image it is evident that above this line, namely towards higher grating frequencies, the topography of the grating lines is not well resolved. Therefore, the minimum grating period was restricted to 650 nm. A comparison of subfigures **c** and **d** shows that the grating topography is not perfectly shaped as in the theoretical volume model. Due to the finite voxel volume, the shape can only be approximated. A deviation from the topography will result in diffraction into unwanted diffraction orders and thus a reduced grating efficiency. However, since all undesired diffraction orders are spatially separated from the spectrometer signal region, they will not interfere with the measurement signal.

4. Noise evaluation for the spectrum measurements

For all spectrum measurements, the noise is evaluated and subtracted in the wavelength range from 490 nm to 690 nm. The noise has a characteristic gradient from red to blue which all single wavelength measurements have in common. In order to quantify the noise per single wavelength measurement $n_{\lambda_i}(\lambda)$, the fitted sinc² function is subtracted from each measurement signal and negative values are set to zero. Subsequently, these noise signals $n_{\lambda_i}(\lambda)$ are weighted and averaged corresponding to the signal strength of the measured spectrum $I_{mn}(\lambda_i)$. The weighted noise $n_{single,w}(\lambda)$ is thus determined as $n_{single,w}(\lambda) = \sum_{\lambda_i} n_{\lambda_i}(\lambda) \cdot I_{mn}(\lambda_i)/(\sum_{\lambda_i} I_{mn}(\lambda_i))$. The weighted noise signal $n_w(\lambda)$ is normalized to the percentage of the noise area per signal area which is determined from the single wavelength measurements as 51% to average. Finally, the spectrum without noise $I_m(\lambda)$ is evaluated as $I_m(\lambda) = I_{mn}(\lambda) - n_w(\lambda)$.

References

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