Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 270 (2007) 336–339
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Frequency selection of supercontinuum ultrashort pulses using a Fresnel zone plate

A. Gürtler [a,*], J.J. Gilijamse [a], A.A.R. Wetzels [a], L.D. Noordam [a], E. Sali [b], M. Bellini [c]

[a] *FOM Institute for Atomic and Molecular Physics, Kruislaan 407, 1098SJ Amsterdam, The Netherlands*
[b] *Dipartimento di Fisica and LENS, Via G. Sansone 6, 50019, Sesto Fiorentino (FI), Italy*
[c] *Istituto Nazionale di Ottica Applicata and LENS, L.go E. Fermi, 6, 50125, Firenze, Italy*

Received 17 January 2006; received in revised form 5 September 2006; accepted 11 September 2006

Abstract

We propose focusing by a Fresnel zone plate into a pinhole as a cost-efficient, rugged component for wavelength selection in femtosecond pulses. We show measurements of the frequency selectivity of a Fresnel zone plate for an ultra-broadband supercontinuum pulse. We verify that our zone plate does not considerably stretch the 65 fs laser pulses in time.

Frequency selective components form an important component of modern tunable laser sources. Examples are gratings or prisms in parametric oscillators and amplifiers, which select the desired wavelength from a white light continuum created by self-phase modulation in materials like sapphire or quartz. Gratings and prisms are the most commonly used elements for wavelength selection in tunable lasers [1] and pulse shapers [2]. In optical parametric amplifiers, the timing of an ultrashort pump pulse with respect to a chirped continuum pulse and phase matching has been employed [3].

Gratings have a high dispersion, but are expensive and very fragile. In addition, their efficiency is much smaller than unity. Prisms, on the other hand, have a low dispersion and broaden short laserpulses. In this paper, we propose Fresnel zone plates (FZPs) as a cost-efficient, rugged component for wavelength selection. FZPs can have a very high damage threshold and do not require propagation through a dispersing medium. The latter property makes FZPs attractive also for the vacuum ultraviolet region of the electromagnetic spectrum, where refractive optics do not exist due to the high absorption of all materials in this spectral region [4].

Fresnel zone plates (FZP) as shown in Fig. 1 consist of concentric solid and open rings with equal surfaces. This implies that with increasing ring radius, the width of the rings decreases. An amplitude FZP blocks part of an incoming plane wave in such a way that the interference of the remaining wavelets leads to a focusing of the beam. The focal distance f_{FZP} of such a structure in the paraxial case is given by [5]:

$$f_{\mathrm{FZP}} = \frac{R_m^2}{m}\frac{1}{\lambda} \tag{1}$$

where R_m denotes the radius of the mth ring and λ the wavelength of the incoming light and R_m^2/m is constant. The FZP used in the experiments described here is made from Molybdenum by electric discharge machining (EDM). It consists of seven rings, the outmost one with a radius of approximately 3.2 mm. The number of rings is limited by the minimum structure size of the machining process, which is 100 μm in our case. Much higher ring numbers and smaller sizes can be reached using lithographic techniques. The focusing properties of FZPs have been investigated theoretically in great detail [6] and

* Corresponding author. Address: Radboud University Nijmegen, High Field Magnet Laboratory, PO Box 9010, 6500GL Nijmegen, The Netherlands. Tel.: +31 24 3653367; fax: +31 24 3652440.
E-mail address: a.guertler@science.ru.nl (A. Gürtler).

0030-4018/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2006.09.029

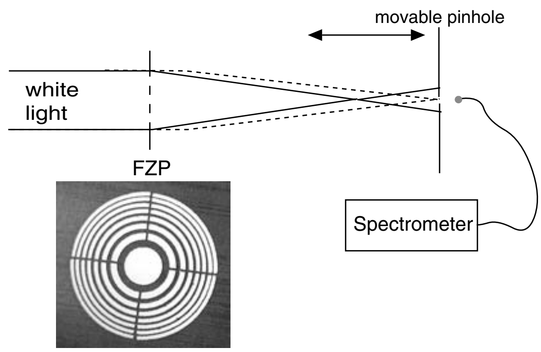

Fig. 1. Experimental set-up. The photo shows an optical image of a Fresnel zone plate consisting of 7 solid and 8 open rings with equal surface. The smallest structures are 100 μm.

attention has been paid to the focusing of ultrashort pulses [7]. An exciting generalization of the FZP which overcomes many of the FZP's limitations is the photon sieve, which is made by appropriately distributing small holes over the Fresnel zones [8,6].

From Eq. (1) it is clear that different wavelengths have different focal distances ($f_{FZP} \propto 1/\lambda$). By placing a small (≈100 μm diameter) pinhole in the focus of a given wavelength, we can select a part of the spectrum, depending on its location in the long focus. Obviously, the central wavelength of the selected spectrum is a function of the distance z between zone plate and pinhole, while the width depends on the waist of the focus and the diameter of the pinhole.

In this paper, we investigate whether FZPs can be used to select a fraction of the bandwidth of an ultrashort laser pulse while keeping a short pulse duration.

The experimental setup is as follows. Ultrashort laser pulses are generated in a Ti:Sapphire oscillator and amplified in a multi-pass amplifier. The system delivers ~65 fs pulses centered around $\lambda = 800$ nm. The laser pulses are focused into a rotating calcium fluoride plate. At a pulse energy of $\lesssim 1$ μJ, a filament is formed by Kerr-focusing. Self-phase modulation gives rise to a broadening of the pulse spectrum and to the emission of a coherent ultrabroadband supercontinuum ranging from 400 to 1000 nm [9–11]. The generated continuum radiation is collimated with a parabolic mirror and sent through the FZP. The frequencies in the continuum are focused at focal distances given by Eq. (1). It should be noted that a FZP, unlike a lens, has multiple higher-order foci at focal distances of $f_{FZP}/3$, $f_{FZP}/5, \ldots$ and anomalous foci at $f_{FZP}/2$, $f_{FZP}/4, \ldots$ [12].

A glass fibre with an entrance pinhole of ≈100 μm is placed along the focal line and couples the light into a spectrometer. For the white light measurements, a filter is used to cut the very strong part of the spectrum around 800 nm in order to avoid saturation of the spectrometer.

Initial measurements were performed at a low power, when just a moderate spectral broadening with a full width at half maximum (FWHM) of about 50 nm is present. The resulting pulses were not transform limited, but we did not try to recompress them as this was beyond the aim of this experiment. Fig. 2 shows the spectrum of the fundamental infrared pulse in the first order focus f_{FZP}. Reducing the diameter of the entrance pinhole to 50 μm did not further narrow the spectrum, consistent with the fact that the size of the focus of a FZP is on the order of the width of the narrowest ring, which is 100 μm [6]. The measured spectra clearly move their center of gravity while moving the pinhole along the focal line while their FWHM remains almost constant and is of the order of 30 nm.

Although one would ideally like to measure the duration of the pulses obtained by slicing the supercontinuum after frequency-selection by the FZP and the pinhole, this is not simple due to their low intensity and due to the lack of suitable equipment to measure the autocorrelation in the visible (hence with a second-harmonic signal in the ultraviolet). What we do instead is to measure the pulse length of the spectrally broadened infrared pulses transmitted through the FZP. Our aim is to verify that the pulse duration is not increased after transmission through the FZP. Of course, this would not be true in the case of much shorter (i.e. less than about 30 fs) pulses, as in this case the reduction of the spectrum below the transform-limited width of 30 nm implies that the pulse duration would indeed increase.

We perform the 800 nm pulse duration measurement by taking a standard second-order non-collinear autocorrelation in a thin BBO crystal. The autocorrelation is performed by splitting the infrared (IR) laser beam after transmission through the FZP and recombining the two pulse replicas inside the BBO crystal at the focus of the FZP. The nonlinear crystal thus replaces the pinhole and acts as a spatial (and consequently spectral) selector.

Fig. 3 shows the autocorrelation trace in the focus of the FZP (dashed line) together with the autocorrelation of the spectrally-broadened laser pulse without the FZP, and using a plain glass lens as the focusing element. The pulse duration of ~65 fs is not appreciably changed by the

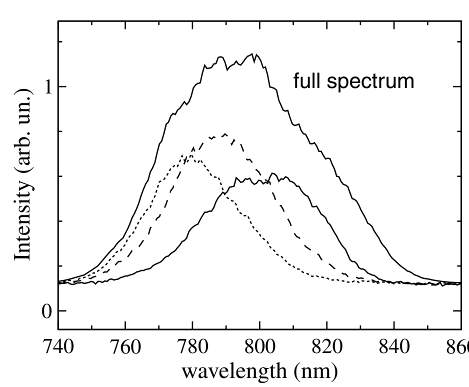

Fig. 2. Spectrum of the infrared laser beam after the FZP and selection with a 100 μm pinhole at 108 cm (solid line), 115 cm (dashed line) and 122 cm (dotted line) from the FZP. The thin line shows the full spectrum (divided by 4).

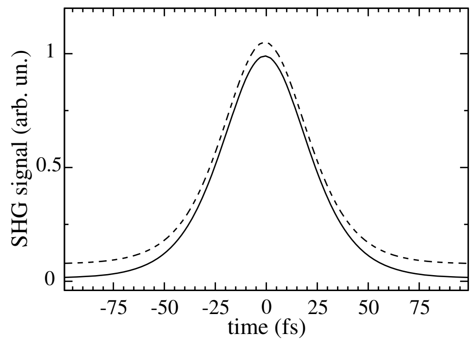

Fig. 3. Fits of a sech^2-function to the autocorrelation traces of the 800 nm pulses focused by a glass lens (solid line) and the FZP (dashed line). The traces are vertically offset for clarity. The pulse duration of ∼65 fs (full width at half maximum) is not considerably changed by the FZP.

Table 1
Focal length f (i.e., distance between the FZP and the pinhole), central wavelength λ_0 and spectral width $\Delta\lambda$ of the selected pulses after the FZP and a 100 μm pinhole

f (cm)	λ_0 (nm)	$\Delta\lambda$ (nm)
64	534	44
68	525	40
69	515	45
70	510	44
72	502	41
74	492	38
76	485	37
78	477	38
80	463	46
82	455	31

FZP for the pulses used in this experiment, indicating that in these conditions the FZP can be used as a frequency-selective element without introducing pulse-lengthening effects.

Fig. 4 shows the spectrum of the white light pulse for various distances in the second order focus $f_{\text{FZP}}/2$ of the FZP. The spectrum is narrowed after the pinhole to a bandwidth of ≈40 nm, and the central wavelength depends on the distance from the FZP. The results are tabulated in Table 1. To evaluate the system's performance as a frequency selector, we make the following estimate. The size of the focus w of light with a wavelength λ_1 at a distance $z_1 = R_m^2/m\lambda_1$ from the FZP along the optical axis (in focus), is a constant of the FZP and given by the width of its thinnest (outer) ring. Another wavelength λ_2, in focus at $z_2 = R_m^2/m\lambda_2$, has at point z_1 a beam size of $w(z_1) = D \cdot |z_1 - z_2|/z_2$ in the geometrical approximation, which is valid if $|z_1 - z_2|$ is sufficiently large. D denotes the size of the incoming beam. A pinhole of size w at a distance z_1, the location of the focus of λ_1, will therefore transmit $\eta = w^2/w(z_1)^2$ of the spectral intensity of the wavelength λ_2. Filling in typical numbers from our experiment ($w = 100$ μm, $\lambda_1 = 492$ nm, $\lambda_2 = 534$ nm, $D = 3$ mm) and using the experimentally determined focal distances yields $\eta \approx 4.5\%$, in reasonable agreement with the experimental findings.

Fig. 5 shows a photograph of a projection of the focal region of green light on a white screen. The lower panels show zoom-outs of the focus in the focal distances of red, orange, green and blue lights. The change in color of the focus is clearly visible by eye.

These results allow us to propose a very simple set-up for frequency-selection of ultrashort pulses across the visible and the near-IR starting from a white-light supercontinuum pulse. The narrow-band light emerges from the pin-hole with roughly the same divergence for all colors. Apart from a FZP and a pinhole, the only other bit of equipment that one needs is a parabolic mirror to be kept

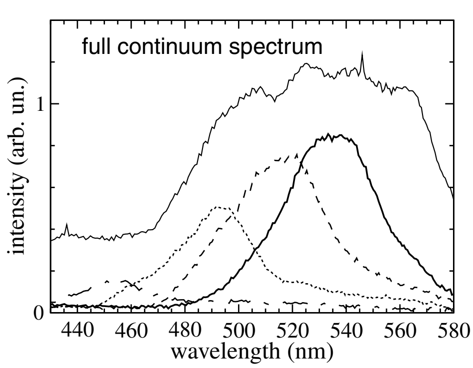

Fig. 4. Spectrum of the short-wavelength portion of the supercontinuum after the FZP and selection by a 100 μm pinhole at a distance of 64 cm (solid line), 69 cm (dashed line), 74 cm (dotted line) and 82 cm (dash-dotted line) from the FZP. The thin line shows the full spectrum (amplitude divided by 2).

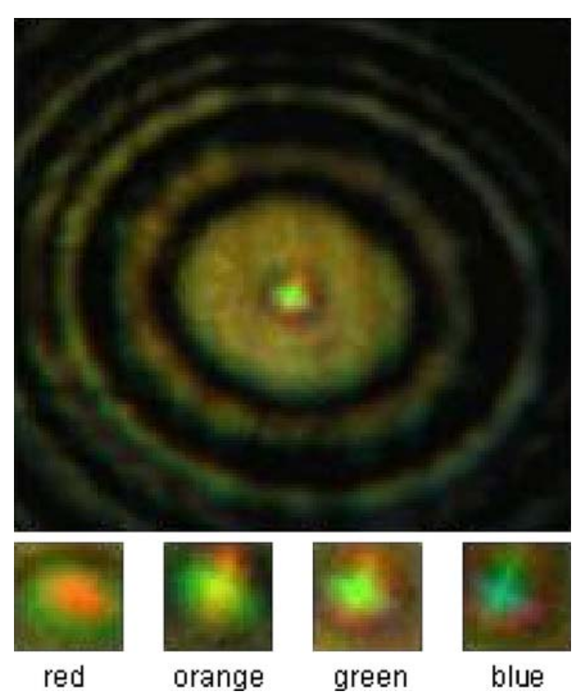

Fig. 5. Upper panel: Photograph of projections of the focal plane of the FZP in the region of the focal length for green wavelengths. Lower panel: Zoom-outs of the center of the focal planes for red, orange, green and blue wavelengths.

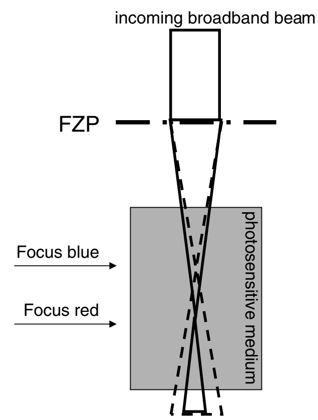

Fig. 6. Schematic representation of a device to simultaneously write and read information stored in wavelength channels of a broadband pulse using a FZP. The information is encoded in channels in the spectrum of the pulse as high or low spectral intensity. Different parts of the spectrum affect different spots in the medium where they are in focus.

at a fixed distance from the pinhole equal to its focal length (which is the same for any wavelength). The frequency-selection device is obtained by simply mounting the pinhole and the parabolic mirror on a translation stage and by moving it along the propagation direction of the supercontinuum beam after the FZP. The distance of the pin-hole from the FZP will determine which frequency-component is selected and later re-collimated by the parabolic mirror. The duration of the selected pulse will be determined only by the width of the transmitted spectrum, as we verified that no additional pulse-lengthening effects are introduced by the FZP.

One can think of many applications of an efficient, rugged and cheap wavelength-selective component for broadband light pulses. As an example we give a scheme for optical storage and readout of information encoded in wavelength channels of a broadband pulse (wavelength division multiplexing). The following situation comes to mind: Information is stored as bits in the spectral intensity of a broadband pulse in channels of width $\Delta\lambda$, where a spectral intensity >0 stands for logic one. This pulse is focused with a high intensity by a FZP into a medium with a low damage threshold. The foci of the wavelength channels will be displaced by an amount Δf given by Eq. (1). Only in channels with logical 1 (high spectral intensity), the intensity will be high enough to induce damage to the medium (see Fig. 6).

If a weak readout pulse is focused by the same FZP into the written medium in such a way that the wavelength λ is focused at a distance f_λ, this wavelength λ will encounter the damaged (thus absorbing or scattering) bit at depth f_λ and be strongly affected by it. The other channels are defocused at this spot, and therefore not affected. In this way, the stored information is re-encoded into the spectral intensity of the broadband pulse. There is no need to re-collimate the resulting pulse. Rather, it can be collected by a collecting optics (e.g. a Winston cone) into a fiber and a spectrometer.

This example describes a simple scheme for data storage and readout using broadband, wavelength-multiplexed light. The analysis of the performance of such a device and the comparison with existing optical storage technologies is beyond the scope of this paper.

In conclusion, we used a Fresnel zone plate to focus ultra-broadband pulses. By moving a pinhole along the focus, we were able to select ~40 nm broad parts of the spectrum. We verified that the FZP does not lengthen pulses as short as 30 fs in the infrared. This suggests that FZPs can be a useful diffractive component in applications of ultrashort and ultra-broadband pulses. Extensions of the FZP concept such as the photon sieve can improve the performance in the future.

Acknowledgements

This work is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie (FOM)", which is financially supported by the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)". Also partially supported by EC JRA contract RII3-CT-2003-506350.

References

[1] T.W. Hänsch, Appl. Opt. 11 (1972) 895.
[2] A.M. Weiner, Rev. Sci. Instr. 71 (2000) 1929.
[3] G. Cerullo, M. Nisoli, S. De Silvestri, Appl. Phys. Lett. 71 (1997) 3616.
[4] C.D. Pfeifer, L.D. Ferris, W.M. Yen, J. Opt. Soc. Am. 63 (1973) 91.
[5] E. Hecht, Optics, fourth ed., Addison Wesley Longman, Inc., Reading, 2002.
[6] Q. Cao, J. Jahns, J. Opt. Soc. Am. A 21 (2004) 561.
[7] R. Ashman, M. Gu, Appl. Opt. 42 (2003) 1852.
[8] L. Kipp, M. Skibowski, R.L. Johnson, R. Berndt, R. Adelung, S. Harm, R. Seemann, Nature 414 (2001) 184.
[9] R.R. Alfano, S.L. Shapiro, Phys. Rev. Lett. 24 (1970) 584.
[10] M. Bellini, T.W. Hänsch, Opt. Lett. 25 (2000) 1049.
[11] Special Issue on Supercontinuum, Appl. Phys. B 77 (2003) 2/3.
[12] J. Higbie, Am. J. Phys. 44 (1976) 929.