Aberration-free high NA focusing in transparent media

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Aberration free focusing inside transparent media is important in microscopy, various techniques of optical data storage and laser microprocessing. By high NA focusing inside a medium there appears essential spherical aberration reducing light energy concentration and lowering physical resolution, the deeper is focusing and higher NA, the stronger is aberration and light scattering. Solution to compensate spherical aberration by deep high NA focusing, for example from 0 to 2 mm in fused silica with NA0.8 without immersion, is suggested in form of the aplanatic objective of patent pending optical design. Composed from air spaced lenses, the objective provides diffraction limited on-axis and off-axis focusing at different depths through setting movable components in optimum for particular depth reciprocal positions. Then, exact compensation of spherical aberration and coma by focusing inside a transparent medium is provided for NA0.8 without immersion. There are presented comparative results of spot size calculations and corresponding microphotographs of processed areas in fused silica by laser radiation focusing at various depths using NA0.8 objectives with and without compensation of aberrations. These results confirm workability of the suggested approach of building high NA aplanatic optics for diffraction limited on-axis and off-axis focusing at different depths.

Keywords: aberration, optical design, aplanatic, microscopy, optical data storage, micromachining

1. Introduction

High numerical aperture (NA) focusing of light inside transparent or partially transparent materials is important technique in microprocessing applications of laser glass cutting, sapphire dicing in LED manufacturing, Si wafer in microelectronics, as well as in various types of microscopy: confocal microscopy [1], fluorescence techniques [2], multi-focus microscopy [3, 4]. Other applications examples are laser-induced refractive index variation of glass [5], nanostructuring in glass for optical data storage [6-10] or polarization converters [11].

A common feature of these techniques is ~1 µm size of focus spots achieved using high-NA objectives or specially designed aspherical lenses which aberration correction is provided for a particular working plane in air or inside transparent medium, for example on back surface of a cover glass; then the spot size in the pre-determined working plane is defined by wave nature of light, i.e. by diffraction limitation. When light focusing at different depths inside the bulk medium there appears spherical aberration [1, 2, 5, 12, 13] and resulting spot size is defined rather by this geometrical aberration - for NA more than 0.5 the resulting focused spot can become several times larger than the diffraction limited one [14]. This has, inevitably, influence on laser energy concentration in laser techniques and reduces physical resolution, contrast and image intensity in microscopy. The aberration induces the shift of effective focus from a nominal focus position [1] - this is very important in confocal microscopy and other measurement techniques. The higher is optics NA or deeper is focusing inside transparent media, the bigger is spherical aberration and, hence, stronger scattering of light energy.

Usual methods of compensation of the spherical aberration are based on applying spatial light modulators (SLM) [12, 15] or adaptive mirrors [16], as well as using objectives with movable group of lenses being shifted by a correction collar [17]. These methods provide good performance and stable results when operating within a pre-determined range of focusing depths; however their technical realizations are rather complicated and don't presume compensating the spherical aberration simultaneously in several working planes separated along optical axis. The last feature is very important in multi-focus microscopy [3, 4] as well as in various multi-focus techniques used in laser cutting and drilling of brittle materials, for example ones based on diffractive multi-focal lenses [18, 19].

Solution to compensate spherical aberration by deep high NA focusing, for example from 0 to 2 mm in fused silica with NA0.8 without immersion, is suggested in form of the aplanatic objective of patent pending optical design with movable components. There are described design features of this optical approach as well as experimental results of focusing in fused silica samples.

2. Spherical aberration by focusing in media

The spherical aberration is very good investigated and described in plenty of literature sources, for example [1, 2, 5, 12, 13, 20, 21]. Let us emphasize on some features important for the purposes of further consideration. Fig. 1 shows typical for focusing in micromachining ray trace of convergent beam by refraction on a flat boundary surface separating air and a transparent medium, for example glass.

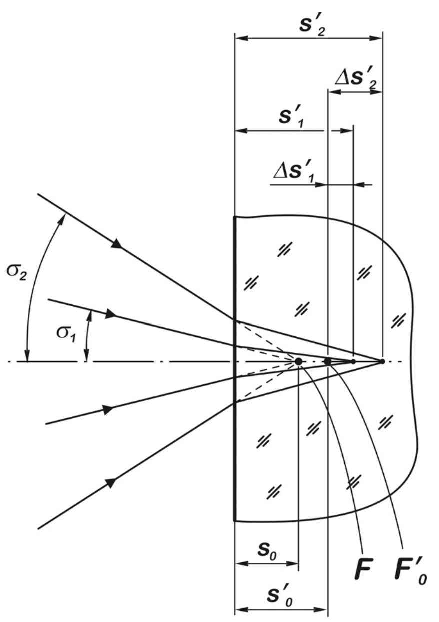

Fig. 1 Spherical aberration $\Delta s'$ induced by focusing in glass.

The light beam propagating from air into glass is focused in virtual point F being located at depth s_0 inside the glass. Paraxial focus F'_0 of the beam after refraction on the flat surface locates at depth s'_0 from that surface. Refraction of a ray on optical surface obeys the well-known Snell's law [20, 21], as result different rays of the beam after refraction intersect optical axis in different points, and the bigger is a ray slope angle the bigger is distance between the paraxial focus F'_0 and the point of optical axis intersection, that distance is called as longitudinal spherical aberration. For rays shown in Fig. 1, slope angles are $\sigma_1 < \sigma_2$, correspondingly distances to intersection points are $s'_1 < s'_2$, and longitudinal aberration $\Delta s'_1$ for the ray with slope angle σ_1 is smaller than $\Delta s'_2$ for the ray with slope angle σ_2. Thus, the longitudinal aberration is positive when light beam propagating from air into glass, i.e. into the medium which refractive index is higher than one of the air. The higher is optics NA or deeper is focusing inside the transparent media, the bigger is longitudinal spherical aberration and bigger is focused spot. This effect is illustrated in Fig. 2 where results of calculations for focusing of laser radiation, λ = 1030 nm, in fused silica at depth 400 μm with different NA are presented:

- the data are given for planes of maximum energy concentration,
- diagrams on top for NA0.4, in the middle – NA0.55, at the bottom – NA0.8,
- spot views are shown on left, the reference black circles are diameters of 1st minimum of Airy disk distribution,
- graphs of energy concentration vs. spot radius are shown on right, the reference black graph corresponds to diffraction limited focusing of Gaussian beam,
- values $d_{80\%}$ are spot diameters where 80% of energy is concentrated,
- values w_{RMS} are root-mean-square (RMS) wave aberration.

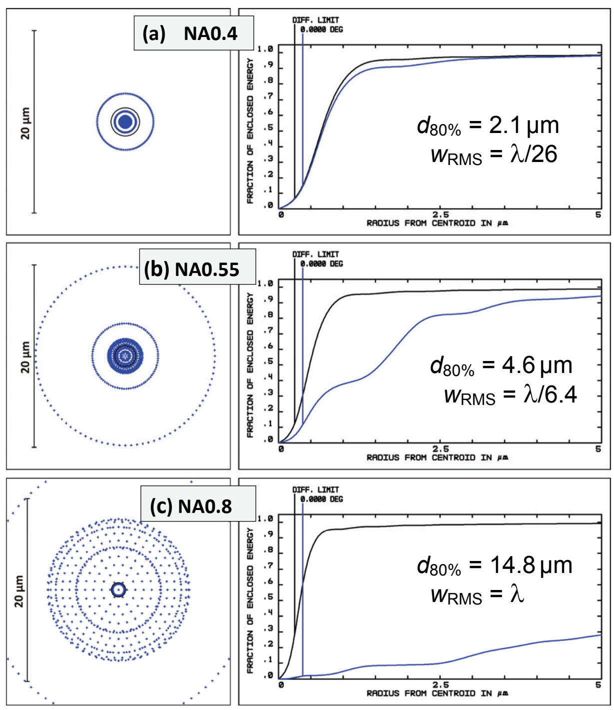

Fig. 2 Focusing at depth 400 μm in fused silica by different NA without compensation of spherical aberration. Explanations in text.

Evidently, light focusability degrades rapidly when increasing NA. Since the main aim of research is providing conditions of diffraction limited focusing it is convenient to evaluate the optical system performance using the Maréchal criterion [20] establishing that the image (or focusing) degradation due to aberrations is negligible when the RMS wavefront deformation (wave aberration) is less than λ/14, where λ is light wavelength, then the physical resolution doesn't depend on geometrical aberrations and is limited by diffraction effects only. The Maréchal criterion corresponds to Strehl ratio 0.8, another specification is also widely used to characterize aberration correction level of imaging or focusing optical systems [20].

The RMS wave aberration values by focusing in fused silica at different depths with different NA at λ = 1030 nm, using objective without compensation of spherical aberration, are presented in the Table 1 and in Fig. 3. Using the Maréchal criterion, the diffraction limited focusing in fused silica at λ = 1030 nm can be provided at depths:

- up to 750 μm with NA0.4,
- up to 180 μm with NA0.55,
- up to 25 μm with NA0.8.

Table 1 RMS wave aberration by focusing in fused silica at different depths with different NA.

Depth, μm	NA0.4	NA0.55	NA0.8	aplanoXX NA0.8
0	0	0	0	0,033
50	0,005	0,020	0,124	0,033
100	0,010	0,039	0,248	0,035
200	0,019	0,078	0,498	0,039
400	0,038	0,156	1,001	0,054
600	0,057	0,234	-	0,071
1200	0,114	0,469	-	-

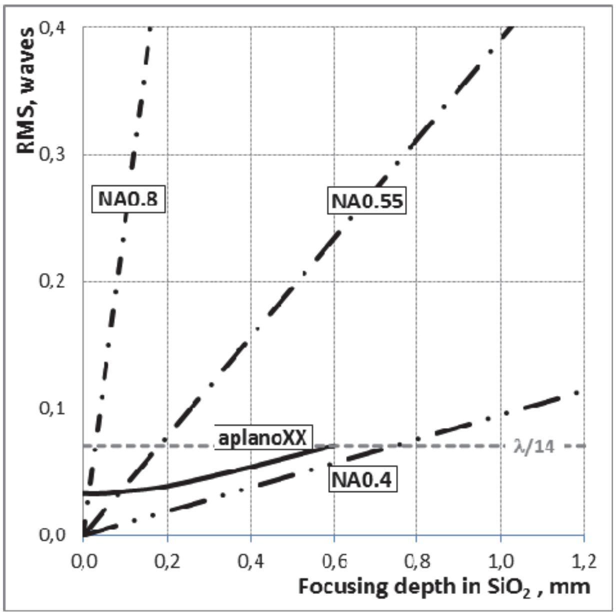

Fig. 3 RMS wave aberration by different conditions of focusing in fused silica.

Increasing physical resolution in microscopy and optical data storage techniques as well as sub-micron focusing in micromachining applications dictate increasing of optics NA [20, 21]. However, simple increasing of numerical aperture strongly reduces the range of depths with diffraction limited focusing. To meet requirements of modern techniques, it is necessary to apply focusing optics supplied with function of compensation of geometrical aberrations, first of all the spherical aberration induced by deep focusing in transparent media. Example of aplanatic objective, realizing this approach, is presented in this paper.

3. Optimized design of focusing objective

Practice of modern laser applications allows formulating some specific requirements to design of laser focusing optics, which are usually not taken into account by developing of ordinary microscope objectives:

- extended working distance,
- resistance to radiation of high peak power ultra-short pulse lasers,
- wide range of focusing depths inside transparent media, for example up to 2 mm in fused silica,
- high NA without immersion,
- stability of operation in presence of misalignments,
- compact and low weight design.

Fig. 4 aplanoXX_NA0.8 - aplanatic objective with compensation of spherical aberration in wide range of focusing depths in transparent media.

The patent pending design approach, realizing fulfillment above mentioned requirements, was applied by developing the aplanatic objectives aplanoXX, photo of one of objectives with NA0.8 is shown in Fig. 4.

The objective design is composed from two lens groups being independently movable along optical axis with respect to each other and the transparent material to be processed. Optimum reciprocal position of those lens groups is defined by minimization of spherical aberration in such a way that the RMS of residual wave aberration doesn't exceed λ/14 (Maréchal criterion). By adjusting the objective to focus at different depths there is no need to change divergence of input beam.

For evaluation of objective performance the results of calculation of wave aberration are presented in the Table 1 and in Fig. 3; they can be easily compared with calculation results for uncompensated focusing with different NA.

The aplanoXX objective, considered in this research, is designed to provide diffraction limited focusing with NA0.8 at depths in fused silica and sapphire up to 600 µm, other design implementations imply extended range of focusing depths, for example up to 2 mm.

To provide resistance to high power laser radiation there are applied air-spaced lenses only (i.e. no cemented lenses) and focusing inside lenses by back reflection from optical surfaces is excluded.

Aplanatic design [21] presumes that aberrations, first of all spherical aberration and coma, are corrected on-axis and off-axis over certain working field and diffraction limited image quality is provided. Therefore the aplanatic objectives aplanoXX are almost insensitive to misalignments by installation. Adaptation of the objective design to particular depth is realized through setting movable components in optimum reciprocal positions. Importance of the aplanatic optical design of objectives and essential performance difference with respect to singlet aspherical lenses is discussed in more details in [14].

Working distance of few millimetres allows convenient operation in industrial equipment and using state-of-the-art auto-focus optical systems.

Being originally designed to operate in air with NA0.8 the aplanoXX objectives can be used with immersion increasing the NA and, hence, physical resolution.

The method of aberration correction applied in design of the aplanoXX objective implies simultaneous compensation of spherical aberration for all working planes within the working range of depths. Thus, optimum conditions for diffraction limited imaging or focusing in multiple planes separated along optical axis is realized. This feature is very important in multi-focus microscopy, as well as in multi-focus DOE-based objectives for microprocessing applications [18, 19].

4. Experimental results of focusing in fused silica

Theoretical considerations about spherical aberration as well as validity of the design approach of aplanoXX objectives were proved experimentally through analysis of processing effects by focusing femtosecond laser radiation of 1030 nm wavelength in fused silica with NA0.55 and NA0.8.

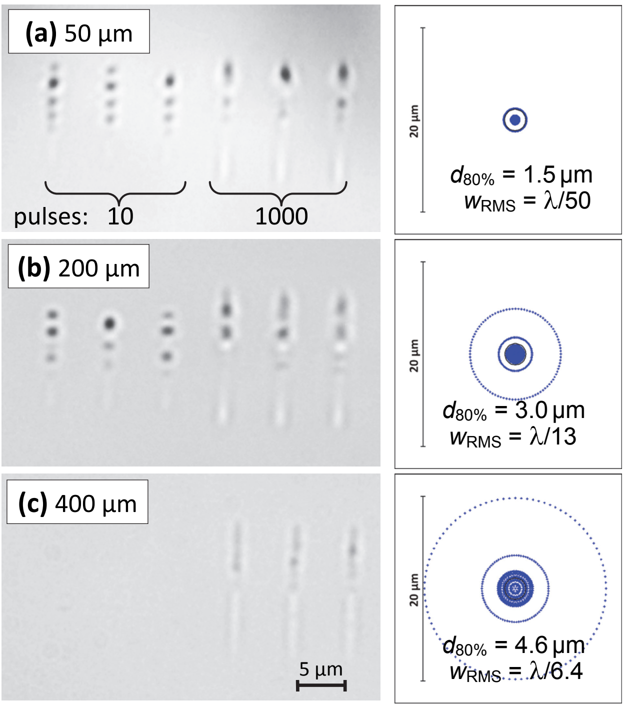

Fig. 5 Focusing the laser radiation (300 fs, 500 kHz, 200 nJ, 1030 nm) in fused silica with NA0.55 at depths: (a) – 50 µm, (b) – 200 µm and (c) – 400 µm. On left – microphotographs of processed zones, on right - views of calculated spots. Layout of pulse groups is shown in top microphotograph.
(Courtesy of University of Southampton)

4.1 Focusing with NA0.55 using aspheric lens

A beam of an ultra-short pulse laser (pulse width 300 fs, repetition rate 500 kHz, pulse energy 200 nJ, wavelength 1030 nm) is focused in fused silica sample at depths 50 µm, 200 µm and 400 µm using aspherical lens optimized for on-axis focusing without spherical aberration in air. During experiments, the aspherical lens was precisely aligned in order to exclude influence of coma and other off-axis geometrical aberrations. Fig. 5 presents, on left, microphotographs of processed zones and, on right, views of the focused spot in plane of maximum energy concentration. Each microphotograph shows 2 groups with 3 processed zones appeared by 10 or 1000 laser pulses. Layout of pulse groups is shown in top microphotograph (a) corresponding to focusing depth 50 µm. For comparison with theoretical data in paragraph 2, focusing is realized with NA0.55 when spot size at depth 400 µm is essentially increased because of spherical aberration.

These experimental results confirm the theoretical considerations:

- diffraction limited focusing is provided for up to ~200 µm depths,
- stability of processing results for depths up to 200 µm is acceptable in applications like laser-induced refractive index variation of glass [5], nanostructuring in glass for optical data storage [6-10] or polarization converters [11],
- almost no processing at depth 400 µm where spherical aberration results in essential scattering of laser energy.

Focusing with NA0.55 allows reliable operation in above mentioned technologies at depths up to ~200 µm. However further development of those technologies requires increasing of focusing depths and higher NA.

4.2 Focusing with NA0.8 using aplanoXX objective

Similar experimental researches were conducted using NA0.8 objective in two operation modes: without and with compensation of spherical aberration induced by focusing of laser radiation inside fused silica. Results are presented in Fig. 6 in form of microphotographs of processed areas as well as calculated views of spots in planes of maximum energy concentration. Laser specifications: pulse width 300 fs, repetition rate 200 kHz, pulse energy 300 nJ, wavelength 1030 nm.

The central microphotograph shows processed areas by 2 groups of 10 and 1000 pulses, 3 multi-pulse shots in each group; the layout of pulses is shown in the inserted microphotograph. The pattern of processed areas is typical in applications like nanostructuring in glass for optical data storage [6-10] or polarization converters [11]. Processing was done for focusing depths from 25 µm to 400 µm with 25 µm step. The set of processed areas, on left from the black arrow, is done by focusing without compensation of spherical aberration. The stepwise set of processed areas, on right from the black arrow, is created by focusing with compensation of spherical aberration using optimum settings on the aplanoXX objective for particular depths.

The sets of microphotographs and calculated spot views on left and right from the central microphotograph are enlarged processed areas for characteristic depths: 50 µm, 200 µm and 400 µm. The spot views contain also calculated values of spot diameters $d_{80\%}$ where 80% of energy is concentrated and RMS wave aberration w_{RMS}, for performance evaluation using the Maréchal criterion.

Comparison of views of processed areas and calculated spots allows making some conclusions:

- by focusing without aberration compensation
  - rapid degradation of focusability at depths more than 50 µm,
  - variable pattern of processed areas at different depths,
  - almost no processing at depth 400 µm,
- by focusing with compensated aberration
  - stable focusability over whole focusing depth range,
  - stable reproduction of processed areas - practically the same view at all depths.

The experimental results confirm theoretical conclusions in paragraph 2. On the other hand, this experiment confirms workability of the design approach applied for compensation of spherical aberration at different focusing depths.

5. Conclusions

Spherical aberration induced by deep focusing inside transparent materials leads to essential degradation of focusability when focusing NA exceeds value 0.4. Compensation of aberration can be realized not only by adaptive optics but also by special optical design of objectives providing diffraction limited high NA focusing in wide range of depths, for example at depths up to 2 mm with NA0.8 in fused silica.

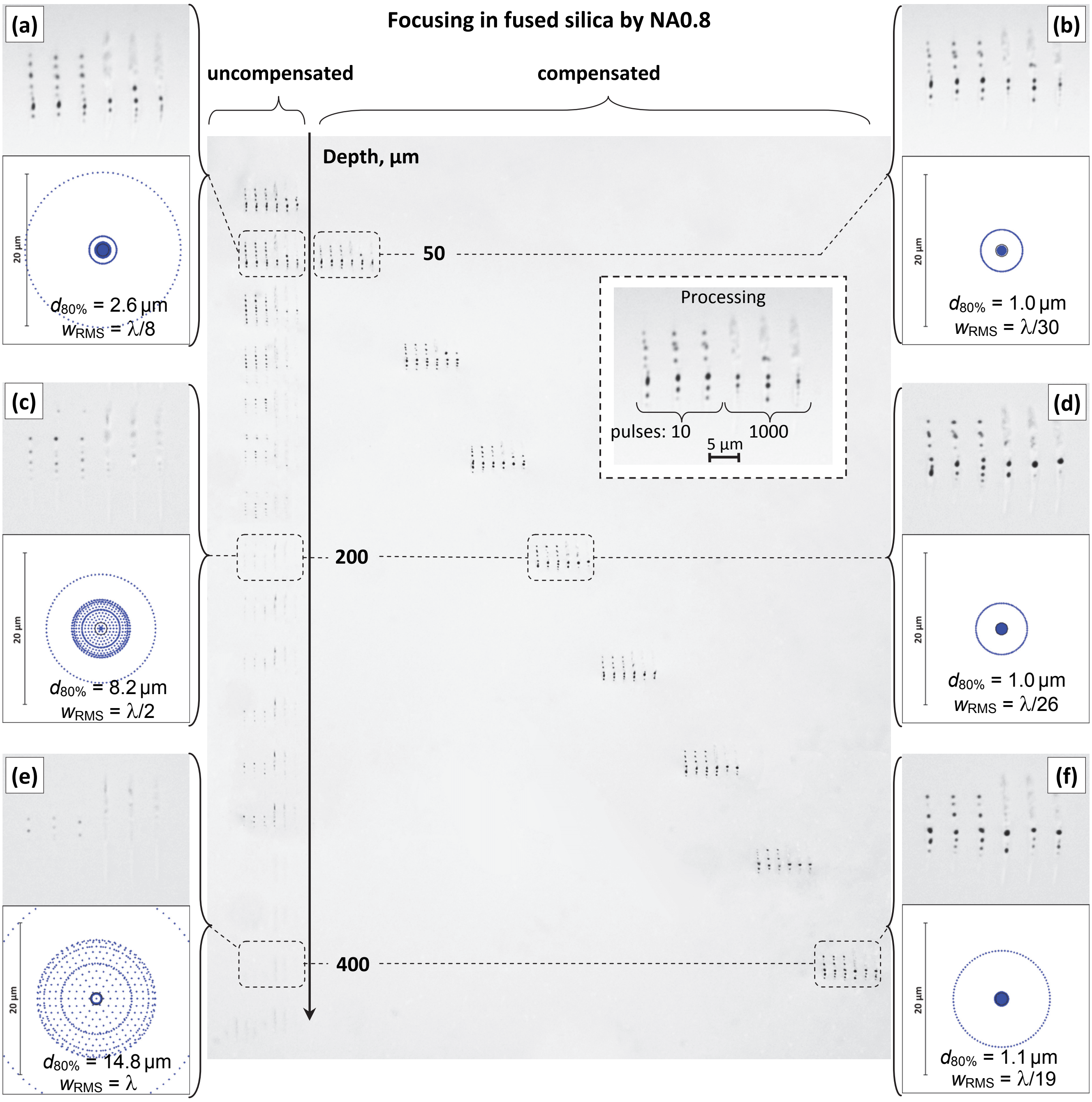

Fig. 6 Focusing the laser radiation (300fs, 200kHz, 300nJ, 1030nm) in fused silica using NA0.8 objective at depths: (a), (b) – 50 µm, (c), (d) – 200 µm and (e), (f) – 400 µm. Views of calculated spots and microphotographs of processed areas: on left – *no* compensation of spherical aberration induced by deep focusing, on right – *with* aberration compensation. Layout of pulse groups is shown in the image inserted in central microphotograph. Values $d_{80\%}$ are spot diameters where 80% of energy is concentrated, w_{RMS} are RMS wave aberration. *(Courtesy of University of Southampton)*

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