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Diffraction limited high NA focusing in transparent media at depth up to 4 mm

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ABSTRACT

Diffraction limited high NA focusing at depth up to 4 mm in transparent media is an important optical task in variety of micromachining applications, nanostructuring, selective laser etching (SLE), optical data storage, and microscopy. By high NA focusing inside glass or another medium, the workpiece becomes a part of the optical system and its flat surface induces significant spherical aberration that reduces the concentration of light energy and physical resolution. The deeper the focusing and the higher the NA, the stronger the aberration and light scattering. The solution to compensate for spherical aberration by deep high NA focusing, for example up to 4 mm in sapphire with NA0.8, is suggested in the form of an aplanatic objective of the patented optical design aplanoXX, supplied with a protective window. The function of spherical aberration of this objective matches the aberration function of the flat optical surface of this medium; therefore, exact compensation of spherical aberration is realized simultaneously with focusing in the medium at a given depth for an arbitrary NA with providing a single spherical wavefront inside the medium.

Due to flexibility of adjustable optical system, the aplanoXX objective can be adapted to operate with fused silica, sapphire, silicon carbide, silicon, glasses, media of eye in applications based on ultra-short pulse lasers in spectra around 1030 nm, 800 nm (Ti:Sapphire), second harmonic (green). The replaceable window protects the optics from damages by particles ejected during material processing. The paper presents an analysis of high NA focusing inside a transparent medium at different depths on the examples of fused silica and sapphire, as well as the experimental application results, confirming performance of the optics.

Keywords: high NA focusing, spherical aberration, microprocessing, optical data storage, Selective Laser Etching, aplanatic optical design

1. INTRODUCTION

High numerical aperture (NA) focusing of light inside transparent or partially transparent media at different depths is important in numerous laser microprocessing techniques realized with the use of ultra-short pulse lasers, for example glass cutting, dicing sapphire in LED manufacturing and Si wafers in microelectronics, slicing SiC[1], Selective Laser Etching[2] (SLE), 3D micro- and nanofabrication[3], waveguide writing[4], nanostructuring in glass for optical data storage[5-9] or polarization converters[10], as well as in various types of microscopy: confocal microscopy[11], fluorescence techniques[12], multi-focus microscopy[13,14]. A common feature of these techniques is ~1 µm size of focus spots achieved with high-NA objectives or specially designed aspherical lenses, the aberration correction of which is provided for a specific working plane in air or inside a transparent medium, for example on the back surface of a cover glass. Then the spot size in the pre-determined working plane is defined by the wave nature of light, that is, the diffraction limit[15-17]. When light is focused at different depths inside the bulk medium, the flat surface of this medium becomes a part of the optical system that introduces spherical aberration[4,11,12,18,19], then the resulting spot size is defined rather by this geometrical aberration - for NA more than 0.5 the focal spot can become several times larger than the diffraction limited one[20]. This inevitably decreases the laser energy concentration and physical resolution, contrast and image intensity. Aberration induces the shift of the effective focus from the nominal focus position[11] - this is very important effect in confocal microscopy and other measurement techniques. The higher the NA of the optics or the larger the focusing depth, the stronger the spherical aberration and light energy scattering.

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Usual methods of compensating spherical aberration are based on the use of spatial light modulators[18,21] (SLM) or adaptive mirrors[22], as well as on the use of objectives with a movable lens group moved along the optical axis by a correction collar[23]. These methods provide good performance and stable operation over a range of focusing depths of several hundred microns, when the wavefront spherical aberration is not large, typically less than 10λ. However, focusing with a high NA at a depth of several millimeters is characterized by order of magnitude larger wavefront aberration values, for example, more than 100λ by focusing with 0.8 NA in fused silica at a depth 2 mm. This, obviously, exceeds the capabilities of adaptive optics. When SLM is used to compensate for wavefront spherical aberration of several wavelengths, the resulting wave surface inside the transparent medium presents a piecewise function that leads to unwanted diffraction effects at the focal point. Optical systems with SLM and adaptive mirrors are rather complex and do not imply compensation for spherical aberration simultaneously in several working planes separated along the optical axis. The latter feature is very important in multi-focus microscopy[13,14] as well as in various multi-focus techniques used in laser cutting and drilling of brittle materials.

Summarizing the requirements to focusing optics in modern scientific and industrial applications: up to 0.8 NA, range of focusing depths 0-4 mm for ps and fs ultra-short pulse lasers at wavelengths of 1550 nm, 1030 nm, 800 nm, 532 nm, with high energy concentration ensured by diffraction limited focusing quality, low sensitivity to misalignments and easy tuning for operation at different depths in the given working range. This paper describes the basic aberration features of the focusing optics and the optical solution in the form of an aplanatic objective of patented optical design[24] with movable components. There are described the design features of this optical approach, as well as the experimental results of focusing in fused silica.

2. ABERRATIONS

Consider aberrations occurring when focusing laser radiation inside transparent media:

- spherical aberration induced by a flat optical surface,
- coma, leading to asymmetry of the focal spot by the tilt of the laser beam or the optics misalignments.

2.1 Spherical aberration by focusing in media

The effect of spherical aberration is well investigated and described in literature[4,11,12,15-19]. Let us emphasize some of the features that are important for laser focusing in micromachining. Fig.1(a) shows a typical ray trace of a convergent beam by refraction on a flat boundary surface separating air and a transparent medium, such as glass.

A beam of light propagating from air into glass is focused at a virtual point F located at a depth s_0 inside the glass. The paraxial focus F'_0 of the beam after refraction on the flat surface is located at a depth s'_0. Refraction of a ray on the optical surface obeys the well-known Snell's law[15,16], as result, different rays of the beam after refraction intersect the optical axis at different points, and the larger the ray slope angle σ, the larger the distance s' between the paraxial focus F'_0 and the point of the ray intersection with the optical axis, this distance is called as the longitudinal spherical aberration $\Delta s'$. For the rays shown in Fig.1(a), $\sigma_1 < \sigma_2$, $s'_1 < s'_2$, therefore, the larger the slope angle σ, the larger the value $\Delta s'$, thus the longitudinal spherical aberration is positive when the light beam propagates from air into glass. The higher the optics NA or the deeper the focusing inside the transparent medium, the greater the longitudinal spherical aberration and the larger the focused spot. This effect is illustrated in Figs.1(b), (c), (d) as the results of calculations of light focusing at $\lambda = 1030$ nm in fused silica at the depth of 400 μm with different NA:

- data for numerical apertures 0.4, 0.55 and 0.8 are given for the planes of maximum energy concentration, corresponding to the minimum root-mean-square wavefront aberration,
- the reference black circles at the spot views are Airy disks (1st minimum of Airy disk intensity distribution),
- the graphs of the energy concentration vs. the spot radius are shown on the right, the reference black graph corresponds to the diffraction limited focusing of the Gaussian beam.

Obviously, the light focusability degrades rapidly with increasing NA. Since the conditions of diffraction limited focusing are considered here, it is convenient to evaluate the optical system performance using the Maréchal criterion[15,17] establishing that the image (or focusing) degradation due to aberrations is negligible when the root-mean-square (RMS) wavefront aberration is less than λ/14, where λ is the light wavelength; then the physical resolution does not depend on geometrical aberrations and is limited by diffraction effects only. The Maréchal criterion corresponds to the Strehl ratio 0.8, which is another widely used characteristic of the imaging or focusing quality of optical systems[15].

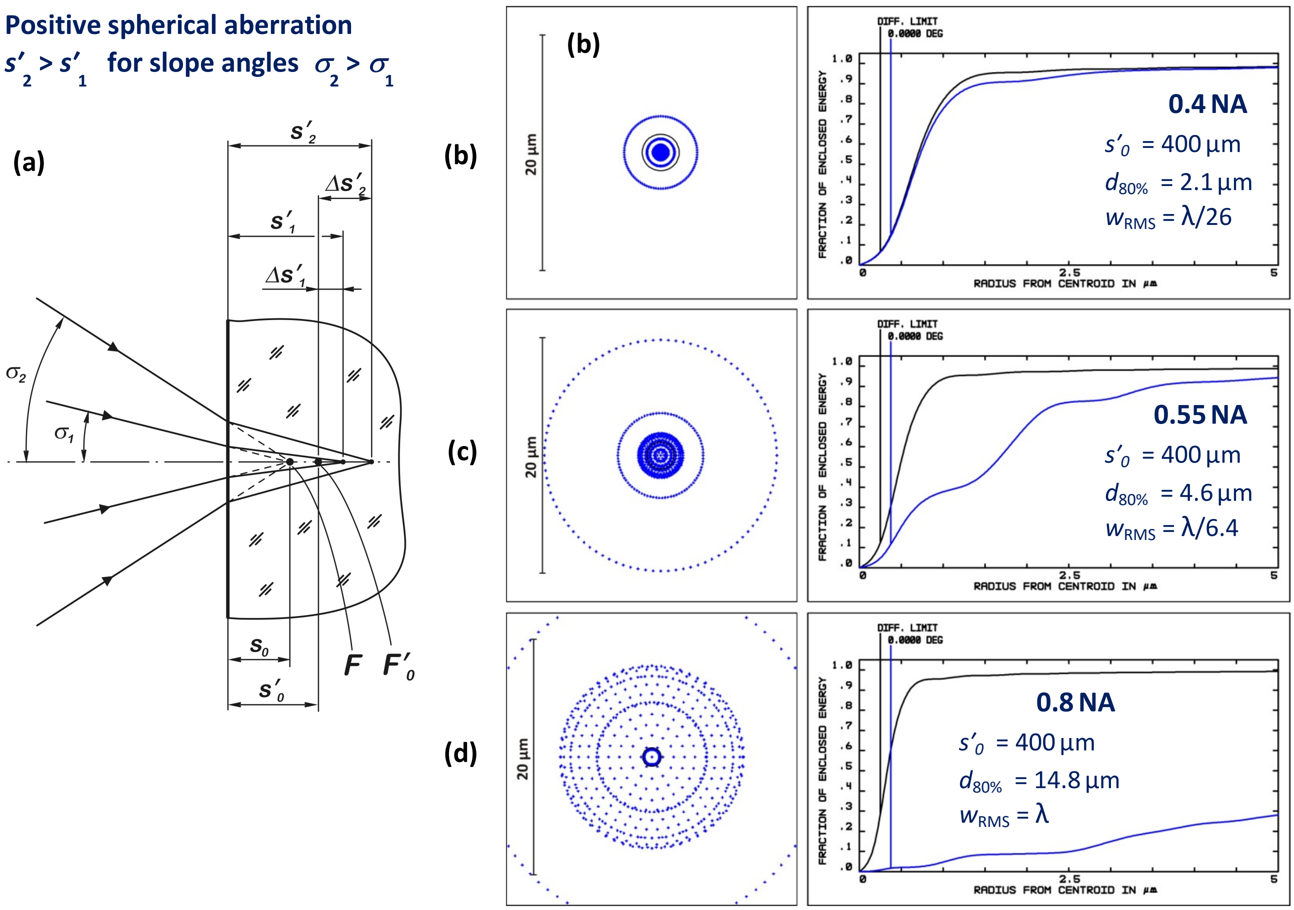

Figure 1 Focusing at a depth of 400 µm in fused silica with different NA, no compensation for spherical aberration: (a) ray trace; the spot views and energy concentration graphs for (b) 0.4 NA, (c) 0.55 NA, (d) 0.8 NA; $d_{80\%}$ is the diameter of the spot, in which 80% of energy is concentrated; w_{RMS} is the RMS wavefront aberration.

The values of RMS wavefront aberration when focusing in fused silica at different depths with different NA at $\lambda = 1030$ nm using an objective without compensation for spherical aberration are presented in Table 1 and Fig.2.

Table 1 RMS wavefront aberration when focusing in fused silica at different depths with different NA, $\lambda = 1030$ nm, the cells when $w_{RMS} > \lambda/14$ are highlighted by red.

Depth, µm	RMS wavefront aberration, in wavelengths			
	0.4 NA	0.5 NA	0.6 NA	0.8 NA
25	0.003	0.007	0.018	0.108
50	0.005	0.014	0.036	0.216
100	0.010	0.028	0.071	0.432
250	0.025	0.071	0.178	1.08
500	0.051	0.142	0.357	2.16
750	0.076	0.213	0.535	-
1000	0.101	0.284	0.713	-

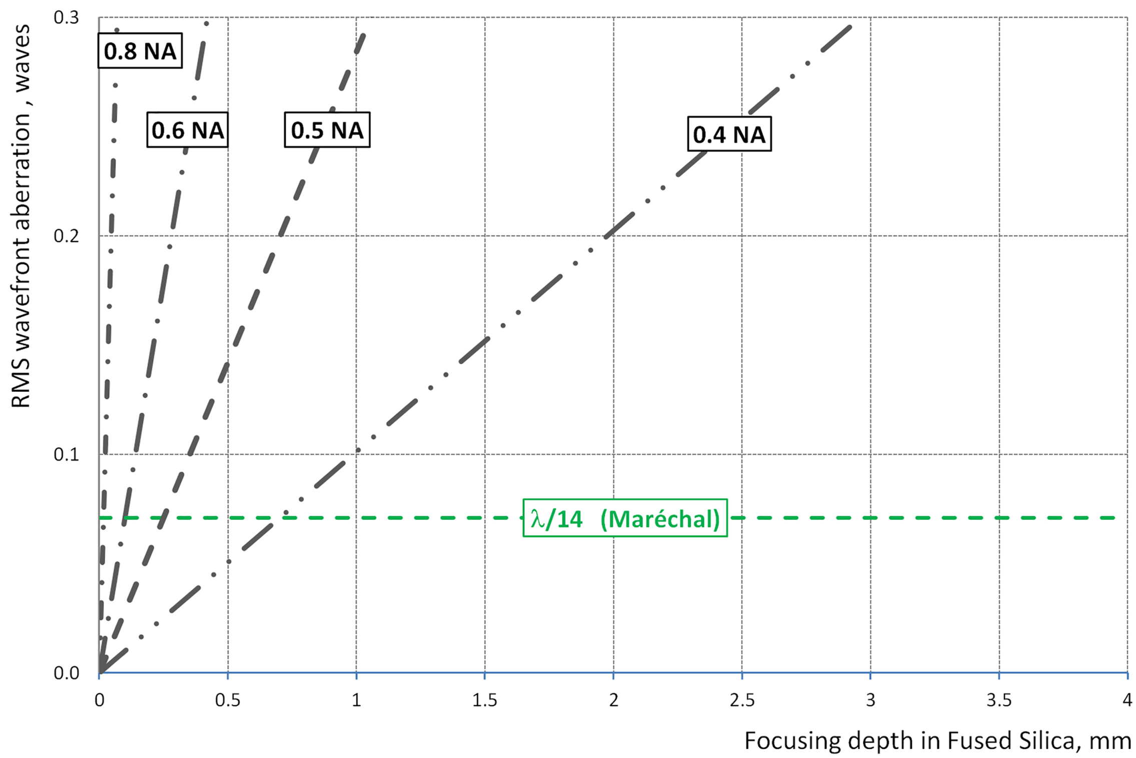

Figure 2 RMS wave aberration when focusing the light of λ=1030nm in fused silica, variable depths and NA.

Using the Maréchal criterion, the diffraction limited focusing is provided at depths:

- up to 750 µm with 0.4 NA,
- up to 250 µm with 0.5 NA,
- up to 100 µm with 0.6 NA,
- < 25 µm with 0.8 NA.

Increasing physical resolution in microscopy and optical data storage techniques, as well as submicron focusing in micromachining applications, dictate increasing the optics NA[15,16]. However, simple increasing of numerical aperture strongly reduces the range of depths with diffraction limited focusing. To meet the requirements of modern techniques, it is necessary to apply focusing optics equipped with a function of compensation for geometrical aberrations, first of all spherical aberration induced by deep focusing in transparent media. An example of aplanatic objective, implementing this approach, is presented in this paper.

2.2 Coma

To ensure stable operation of focusing optics in industrial equipment and to reduce the sensitivity to misalignments, which are inevitable in practice, it is necessary to correct not only on-axis spherical aberration, but also to minimize off-axis aberrations in a certain field of view. This topic is considered in detail in the special literature on the optical system design[15-17]. An important conclusion for practice is that the optical design of the focusing system should be *aplanatic*, i.e. satisfy the so-called Abbe sine condition, which practically means simultaneous minimizing spherical aberration and coma aberration. This condition is fulfilled obligatory in the microscope objectives; therefore, these multi-lens optical systems are insensitive to misalignments and provide easy and simple installation and adjustment in laser equipment and experimental setups. Some objectives[23] are equipped with the function of compensation of spherical aberration that occurs when focusing inside transparent media by moving the lens group by the collar; however, the range of focusing depths is usually few hundred of microns. On the other hand, as multi-lens optical systems developed for microscopy

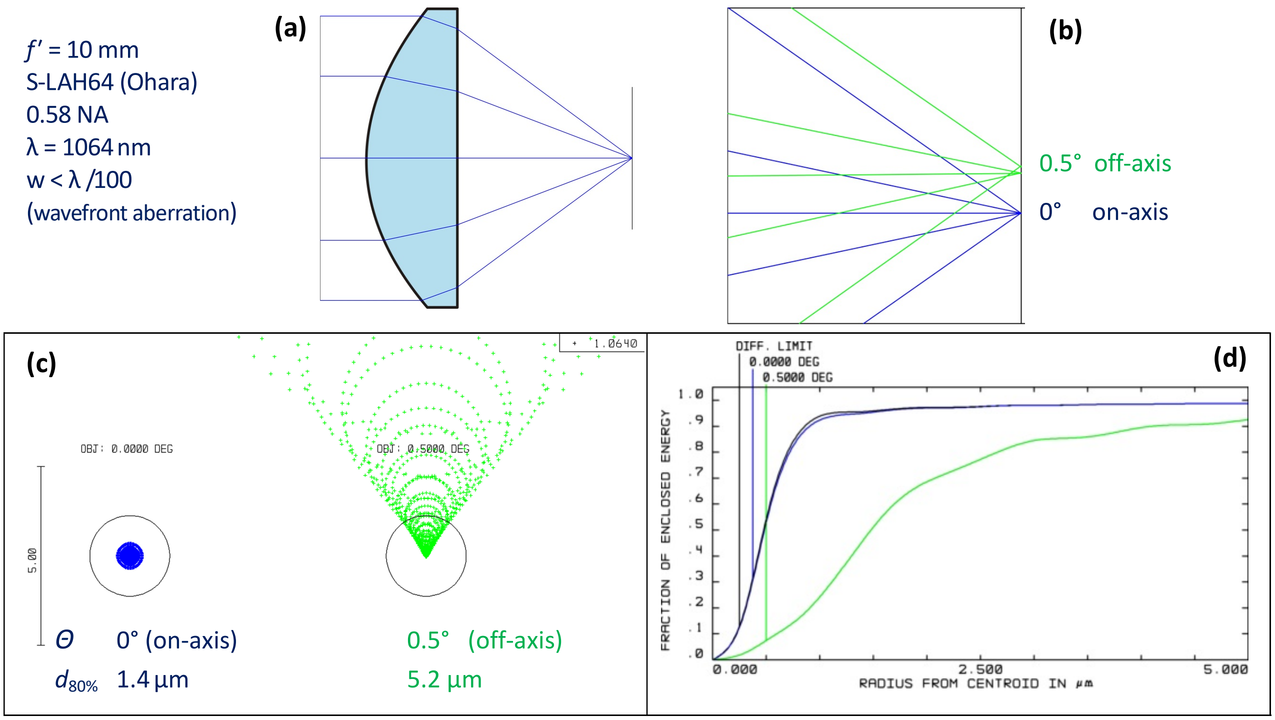

Figure 3 Laser beam focusing by aspheric lens on-axis, 0°, and off-axis, 0.5°: (a) the lens view, (b) ray trace near the focal plane: blue rays on-axis, green rays off-axis, (c) view of spots in the focal plane, (d) graphs of energy concentration.

imaging, the design of which presumes use of thick and cemented lenses, the objectives are characterized by limitation of applicable laser power and are not suited for applications based on the high power ultra-short pulse lasers.

Aspheric lenses are widely used for focusing the laser beams, especially with powerful lasers. Most often, the lenses are implemented as plano-convex lenses with an aspherical convex surface that provides complete correction of spherical aberration, so the lenses are *unaberrated* on axis. However, the optical designs of majority of lenses are *not aplanatic*, therefore are characterized by significant coma and high sensitivity to misalignments. This is illustrated in Fig.3, which shows focusing of on-axis and off-axis beams by the aspheric lens of 10 mm focal length with 0.58 NA.

The aspheric lens is unaberrated on-axis when focusing in air, but is not aplanatic and therefore exhibits significant coma in off-axis beams: the asymmetry of the convergent off-axis beam near the focal plane in Fig.3(b), the typical comma-shaped spot in Fig.3(c), the significantly reduced energy concentration in Fig.3(d). Considering the spot diameters $d_{80\%}$, where 80% of the energy is concentrated, in Fig.3(c), the diameter value for the off-axis spot is more than 3.5 times larger than that of the on-axis spot, thus by switching from the on-axis spot to the off-axis spot the intensity drops more than 10 times! Since the angular error of 0.5° is quite probable when installing and adjusting an optical system, this aspheric lens is very sensitive to angular misalignments.

Summarizing the consideration of aberrations, one can conclude that the optimal focusing optical systems for modern laser techniques should have an aplanatic design presuming the simultaneous minimization of spherical aberration and coma. This aplanatism should be performed over the entire working range of focusing depths inside transparent media. The solution for industrial applications based on high-power lasers in the form of an aplanatic objective with the function of compensation of spherical aberration induced by deep high NA focusing inside transparent media is considered in next section.

3. aplanoXX – OBJECTIVE FOR HIGH NA FOCUSING

Practice of modern laser applications

- Cutting of glass, fused silica, sapphire, Si, SiC,
- Slicing SiC, sapphire,
- Selective Laser Etching,
- 3D micro- and nanofabrication,
- Waveguide writing,
- Nanostructuring in glass for optical data storage,
- Recording polarization converters,
- Microscopy,

allows formulating the specific requirements to the design of laser focusing optics:

- aplanatic design – free of coma and spherical aberrations over entire range of focusing depths,
- compensation of spherical aberration induced by focusing inside transparent media
- wide range of focusing depths: up to 4 mm in fused silica,
- high NA up to 0.8, without immersion,
- extended working distance,
- high transmission and resistance to radiation of high peak power ultra-short pulse lasers,
- operating wavelengths: 1030 nm, 800 nm, 515 nm,
- insensitive to misalignments - stability of operation in the case of angular misalignments,
- protective window – important to avoid contamination of optics, replaceable,
- compact and low weight design.

The solution is suggested in the form of the aplanatic objective aplanoXX of the patented optical design[24], equipped with a replaceable protective window, see Fig.4 and Table 2. The function of spherical aberration of this objective matches to the aberration function of the flat optical surface of a transparent medium; therefore, exact compensation of spherical aberration is realized simultaneously with focusing in the medium at a given depth for an arbitrary NA, with providing a single spherical wavefront inside the medium. To ensure resistance to high power laser radiation, only air-spaced lenses are applied (i.e. no cemented lenses) and focusing inside the lenses by back reflection from optical surfaces (ghosts) is excluded. The replaceable window protects the optics from damages by particles ejected during material processing.

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

Table 2 Specifications of aplanoXX_NA0.8

Numerical aperture	0.8		
Clear Aperture	20 mm		
Focal length	12.5 mm		
Protective Window	D12, replaceable		
Working Distance	2.5 mm, (1.6 mm with window D12)		
Focusing depth	0 ... 4 mm		
Spectral band, nm	_1030:	_800:	_515:
	1020 - 1100	770 - 900	510 - 545
Angular FOV	± 0.3°		
Max. pulse energy	100 mJ at 5 ns / 300 µJ at 1 ps		
Mounting	C-Mount (1”-32 UN 2A)		
Diameter / Length	44 mm / 54 mm		

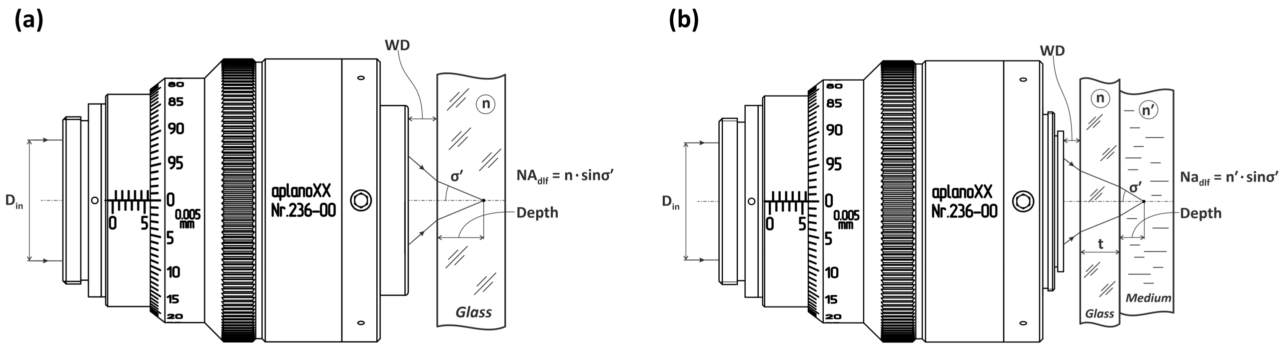

Figure 5 Examples of operation of the aplanoXX_NA0.8:
(a) focusing inside a transparent medium, (b) focusing inside a medium after a Glass Plate.

Due to flexibility of the adjustable optical system, the aplanoXX objective can be adapted to work with fused silica, sapphire, silicon carbide, silicon, glasses, media of eye in applications based on ultra-short pulse lasers in spectra around 1030 nm, 800 nm, 515 nm. The optical design can also be adapted to other spectra. The higher the refractive index of the transparent medium, the larger the range of focusing depth is achieved, for example, the maximum depth in silicon carbide is about 20% larger than in fused silica. As shown in Fig.5, a transparent media can be either a single workpiece, Fig.5(a), or a multi-layer structure, Fig.5(b). Originally designed to operate in air with 0.8 NA, the aplanoXX objectives can be used with immersion increasing the NA and hence the physical resolution. The working distance of more than 2 mm allows easy and simple installing in industrial equipment and using state-of-the-art auto-focus optical systems.

The method of aberration correction applied in the design of the aplanoXX objective implies simultaneous compensation of spherical aberration for different working planes within the working range of depths. Thus, optimal conditions for diffraction limited imaging or focusing simultaneously in multiple planes separated along optical axis are realized. This feature is very important in multi-focus microscopy[13,14], as well as in various multi-focus techniques in micromachining.

The values of RMS wavefront aberration when focusing a laser beam at $\lambda = 1030$ nm using aplanoXX_NA0.8 in fused silica at different depths with different NA are presented in Table 3 and Fig.6, which are expanded versions of Table 1 and Fig.2.

Table 3 RMS wavefront aberration when focusing in fused silica at different depths with different NA, $\lambda = 1030$ nm, the cells when $w_{RMS} > \lambda/14$ are highlighted by red.

Depth, μm	RMS wavefront aberration, in wavelengths					
	Ordinary objective				aplanoXX NA0.8	
	0.4 NA	0.5 NA	0.6 NA	0.8 NA	0.6 NA	0.8 NA
25	0.003	0.007	0.018	0.108	0.001	0.002
50	0.005	0.014	0.036	0.216	0.001	0.002
100	0.010	0.028	0.071	0.432	0.001	0.002
250	0.025	0.071	0.178	1.08	0.002	0.010
500	0.051	0.142	0.357	2.16	0.004	0.029
750	0.076	0.213	0.535	-	0.007	0.051
1000	0.101	0.284	0.713	-	0.010	0.076
1500	0.152	0.355	1.070	-	0.018	0.142
2000	0.203	0.567	1.307	-	0.028	0.223
2500	0.253	-	-	-	0.039	0.313
3000	0.304	-	-	-	0.052	-
3500	0.354	-	-	-	0.07	-
4000	0.405	-	-	-	0.10	-

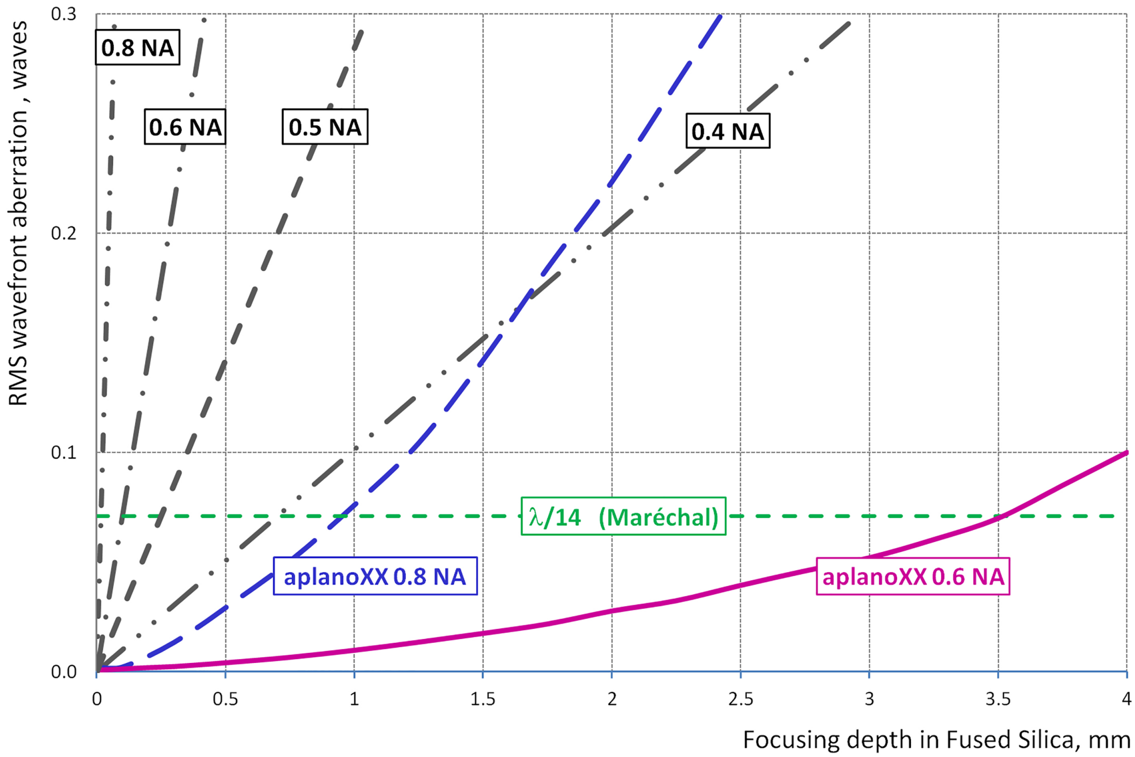

Figure 6 RMS wave aberration when focusing the light of λ=1030nm in fused silica, variable depths and NA, with ordinary objectives without compensation of spherical aberration and with aplanoXX_NA0.8.

Using the Maréchal criterion, the diffraction limited focusing in fused silica is provided at depths:

- with ordinary objective
  - < 100 µm with 0.6 NA,
  - < 25 µm with 0.8 NA,
- with aplanoXX_NA0.8
  - < 3.5 mm by 0.6 NA,
  - < 1 mm by 0.8 NA.

Obviously, the aplanoXX_NA0.8 objective significantly expands the range of diffraction limited focusing depths inside transparent media, with the flexibility to adapt to work with various media at different depths. One more important feature is the capability not only to compensate for spherical aberration induced by deep focusing, but also over- and under-compensating the aberration to provide specific conditions of light focusing and realize new energy distributions in the focused spot; this allows specific material processing effects to be achieved.

4. EXPERIMENTAL VALIDATION

Experimental researches were conducted at the University of Southampton to prove the above considerations and demonstrate capabilities of the optical design approach implemented in the specialized objective aplanoXX_NA0.8 for focusing in transparent media with compensating spherical aberration induced by the workpiece flat surface. Conditions:

- focusing inside fused silica at the depths of up to 400 µm with the step of 25 µm,
- two operation modes: *no* and *with* compensation of spherical aberration induced by the flat surface,
- laser specifications: pulse width 300 fs, repetition rate 200 kHz, pulse energy 300 nJ, wavelength 1030 nm,
- multi-pulse shots at each depth.

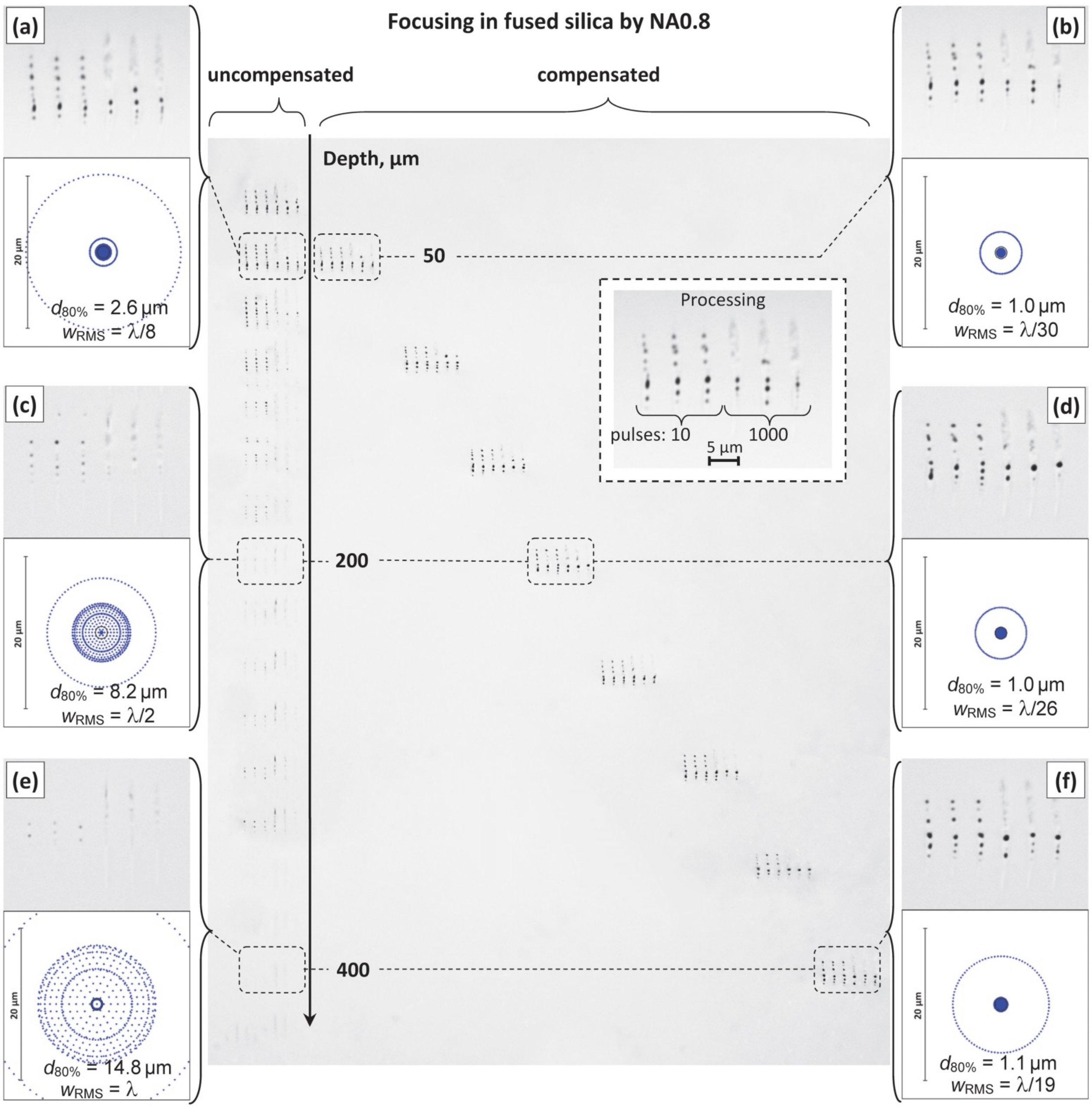

Figure 7 Focusing the laser beam (300fs, 200kHz, 300nJ, 1030nm) in fused silica using the aplanoXX_NA0.8 objective at depths: (a), (b) – 50 µm, (c), (d) – 200 µm and (e), (f) – 400 µm. Views of calculated spots and microphotographs of processed areas: on the left – *no* compensation of spherical aberration induced by deep focusing, on the right – *with* aberration compensation. Layout of pulse groups is shown in the image inserted in the central microphotograph. Values $d_{80\%}$ are the spot diameters where 80% of energy is concentrated, w_{RMS} are RMS wave aberration. *(Courtesy of University of Southampton)*

The results are presented in Fig. 7 in the form of microphotographs of the processed areas, as well as calculated views of spots in the planes of maximum energy concentration. The inserted microphotograph marked "Processing" presents layout of pulses in the processed areas: 2 groups of 10 and 1000 pulses, 3 multi-pulse shots in each group. The pattern of processed areas is typical for applications like nanostructuring in glass for optical data storage[5-9] or polarization converters[10]. The set of processed areas to the left of the black arrow is done with the *uncompensated* focusing - without compensation of spherical aberration. The stepwise set of processed areas to the right of the black arrow relates to the *compensated* focusing, when spherical aberration is compensated using the optimal settings on the aplanoXX_NA0.8.

The sets of microphotographs and the calculated spot views in the left and right columns present enlarged processed areas for characteristic depths: 50 μm, 200 μm and 400 μm. To evaluate performance using the Maréchal criterion, the calculated values of the spot diameters $d_{80\%}$, where 80% of the energy is concentrated, and RMS wavefront aberration w_{RMS} are given in the spot views. Comparison of the presented results allows making some conclusions:

- by the *uncompensated* focusing (no aberration compensation), Figs.7(a),(c),(e)
  - rapid degradation of focusability at depths of more than 50 μm,
  - variable pattern of the processed areas at different depths,
  - almost no processing at depth of 400 μm, Fig.7(e),
- by the *compensated* focusing, Figs.7(b),(d),(f)
  - stable focusability over the entire range of focusing depths,
  - stable reproduction of processed areas - practically the same appearance at all depths.

The experimental results confirm the capabilities of the optical design approach implemented in the specialized objective aplanoXX_NA0.8 for focusing in a wide range of depths inside transparent media with compensation of spherical aberration induced by the flat surface of the workpiece.

5. CONCLUSIONS

Spherical aberration induced by deep focusing inside transparent materials leads to essential degradation of focusability when focusing NA exceeds value 0.4. Diffraction limited high NA focusing in transparent media at depths up to 4 mm can be realized by the specialized objectives with aplanatic optical design, which is free of coma and spherical aberrations over entire range of focusing depths, and providing compensation of spherical aberration induced by the flat optical surface when focusing inside the transparent medium. The objective aplanoXX_NA0.8 implemented according to this design approach ensures diffraction limited focusing with NA0.8 in wide range of depths up to 4 mm in fused silica, optical glasses, sapphire, silicon, silicon carbide and other brittle materials, including multi-layer composition of materials. Experimental researches confirm effectiveness of this new optical design approach.

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