Focal Plane Speckle Patterns for Compressive Microscopic Imaging in Laser Spectroscopy

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***Abstract*— Speckle patterns arise due to interference of many coherent wavefronts with random phases. The patterns can serve as a means of random encoding of scenes for compressive imaging in laser spectroscopy, as is has been demonstrated for the far-field speckles. However, the use of far-field speckle patterns limits resolution of the imaging. Here we present a study of speckle patterns in the proximity of the focal plane of a lens, which can provide an access to speckle patterns on the micrometer scale. We demonstrate the possibility to obtain a scaled-up reference pattern and we also investigate correlation between speckle patterns in different positions close to the focal plane. Finally, we demonstrate single-pixel hyperspectral imaging based on focal plane speckles and discuss their other possible applications.**

Keywords—laser speckle pattern; lens focal plane; random pattern correlation; compressive imaging.

I. Introduction

Laser spectroscopy represents a broad range of methods used to study materials or phenomena by means of laser light.[1] A typical example can be the photoluminescence spectroscopy or Raman spectroscopy. Imaging in laser spectroscopy is a natural step forward, which is essential for understanding processes in structured inhomogeneous samples, such as biological tissues or various semiconductor structures.[2], [3]

A number of approaches can be used for imaging in laser spectroscopy. The approaches can be divided into two main groups: (i) acquiring image by using an array detector, (ii) sample scanning. Both groups suffer from certain drawbacks. Group (i) requires imaging optics and a 2D detector with sufficient noise level and resolution, which can be problematic in some unusual spectral areas (mid/far-infrared, terahertz spectroscopy, …) or for some experiments acquiring subtle signals, such as pump-probe technique. Group (ii) requires extensive acquisition time, since the measurements in laser spectroscopy are often lengthy. A relatively short single acquisition of 1 s leads for a 100×100 pixel image to the total acquisition time of almost 3 hours.

Use of compressive imaging can be an answer to the above mentioned issues.[4] In our previous work, we have demonstrated a simple implementation of compressive imaging (namely single-pixel camera) into laser spectroscopy.[5]–[7] The single-pixel camera (SPC) technique makes is possible to computationally reconstruct an image based on illumination of a scene with a set of known random encoding patterns and by recording the total light intensity.[8] The implementation presented by our group uses the coherent nature of the laser light to produce random patterns, the so-called laser speckles, which can be used as the encoding pattern. A laser speckle pattern arises due to interference of many wavefronts with a random phase, for instance, in the case of a laser beam being transmitted through a diffuser.

In general, our work, together with other approaches using speckle patterns, is employing the so-called far-field speckle pattern.[5], [9] The "far-field" regime corresponds to the fact that the speckle pattern intensity varies with the direction, i.e. for various parallel planes we obtain an identical patterns with a different scaling. This feature is very useful for its application in SPC, since it is simple to acquire a reference image of the pattern. However, the far-field regime imposes limitations on the diffuser-scene distance. This leads to a high mean size of speckles, which in turn determines resolution of SPC based on such random patterns, as we showed in our previous work.[5] Therefore, the use of speckles in the far-field regime significantly limits resolution of the resulting SPC.

In this article we demonstrate an approach to obtaining known speckle patterns on the micrometer scale. We employ the fact, that imaging of a plane wave by using a lens creates Fourier transform of the plane wave intensity profile in the focal plane (FP) of the lens. Moreover, the Fourier image of the plane wave is scaled proportionally to the focal length of the lens.

We show that refocused far-field laser speckles can provide us with fine random patterns with a high spatial resolution. The patterns can be correlated to the reference case with a different magnification. This can be used for single-pixel camera microscopic imaging, as we demonstrate in this articles. Moreover, the focal plane speckles are sensitive to the depth, thus opening possibility for a three-dimensional imaging of a scene and other possible applications.

II. Experimental methods

Scheme of the used experimental setup is depicted in Fig. 1. The speckle patterns were studied by using a 488 nm laser (Sapphire LP, Coherent) focused on a diffusor (ground glass) on a motorized stage. The resulting speckle field was collimated in the far-field regime, so that a patterned speckle "beam" was acquired. The beam was split into two beams,

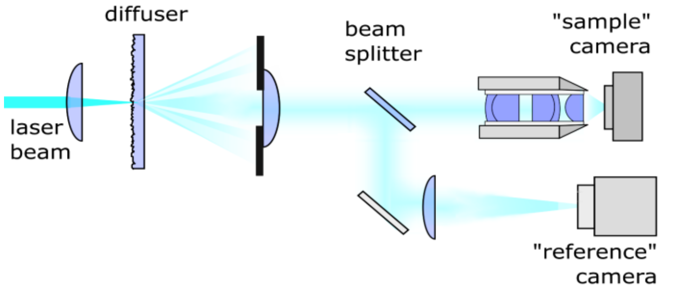

Fig. 2. Scheme of the used experimental setup.

which we will refer to as “reference” and “sample” beam. Both the transmitted (sample) and the reflected (reference) speckles were refocused. The reference part was weakly focused by a $f = 20$ cm lens. The sample part was focused by various lenses, including microscope objective, doublet, plan-convex lens, etc. Both sample and reference speckle patterns were recorded on cameras. The sample camera (IDS UI-1490LE-M-GL) was placed on a motorized stage in order to allow for scanning across the lens FP. A low-resolution reference camera (IDS UI-3370CP) was placed in the speckle pattern focal plane or close to this position.

III. Speckles in the Focal Plane

A collimated far-field speckle pattern can be approximated as a plane wave with a random distribution of intensity $I(x, y)$. We assume that the laser light is nearly monochromatic with wavelength λ. If the pattern is imaged by an ideal lens, the resulting image in the FP $F(x', y')$ can be evaluated in the paraxial approximation as being proportional to the 2D Fourier transform of the image: [10]

$$F(x', y') \propto \iint_{x,y} I(x, y) \exp\left[\mathrm{i}\frac{2\pi}{\lambda f}(xx' + yy')\right] \mathrm{d}x\,\mathrm{d}y \quad (1)$$

According to the equation, focusing of a collimated speckle pattern by using various lenses with varying focal lens f will, in this idealized case, lead to identical random images, which will be scaled according to the lens magnification. However, since we apply a number of assumptions and simplifications, namely light monochromaticity, aberration-free lens imaging, paraxial approximation, the real image will divert from this idealized case. It is, for instance, well known that speckle pattern contrast is considerably affected by lens aberrations.[11], [12]

It is worth noting, that the properties of speckles in FP can be studied by using a numerical simulation, which is, however, very computationally costly.[13] Therefore, we carried out an experimental study, which is also important, as it includes also all inevitable sources of experimental imperfections, such as misalignment of optics from the ideal case.

IV. Results and Discussion

We studied firstly properties of a refocused far-field speckle pattern. The patterns were scanned along the z-axis close to the FP (see Fig. 2A). For each position of the camera we recorded an image and evaluated center and radius $w(z)$ of the speckle pattern. Radii of patterns for various camera positions were fitted by using width of a Gaussian beam:

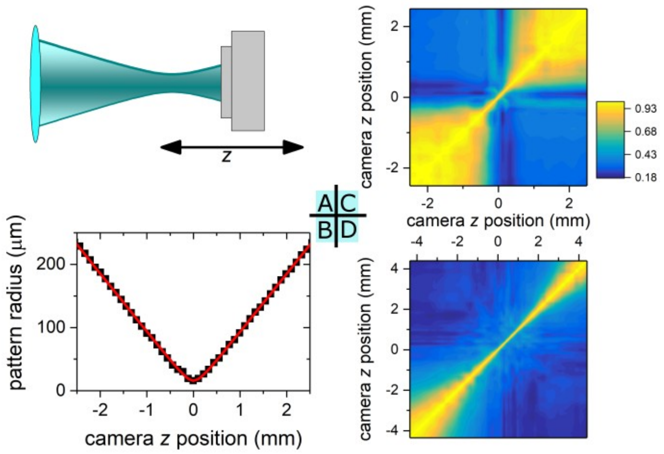

Fig. 1. A) Camera positioning across the lens focal plane denoted as a "z" axis; B) Determined pattern radii (black squares) fitted by Gaussian beam radius dependence (red line); C-D) Degree of correlation between speckle patterns obtained for a various camera position for a microscopi objective (C) and a weakly focusing lens (f=15 cm) (D).

$$w(z) = w_0\sqrt{1 + \left(\frac{z - z_0}{z_R}\right)^2}, \quad (2)$$

where the beam waist radius w_0, the beam waist position z_o, and the beam Rayleigh range z_R were left as fitting parameters. The fit described our patterns very well and enabled us to precisely determine scaling of a speckle pattern in each camera position.

We employed the obtained dependence to rescale all patterns (for various z-positions) onto the same scale. The target resolution was set according to the smallest pattern, in order to avoid artefacts connected to the image interpolation. The unified scale of patterns enabled us to determine the level of correlation $C_{k,l}$ between two patterns $F_k(x, y)$ and $F_l(x, y)$ as:

$$C_{k,l} = \frac{\sum\sum_{x,y}[F_k(x,y) - \langle F_k\rangle]\,[F_l(x,y) - \langle F_l\rangle]}{\sigma_k \sigma_l}, \quad (1)$$

where σ_k denotes the standard deviation of pattern F_k.

We carried out the measurement for two largely different cases with a different Rayleigh range – a microscope objective (Fig. 2C) and a weakly focusing lens (Fig. 2D). In both cases we can clearly observe transition from the far-field speckle patterns, where the pattern is only scaled with the z-axis, into the FP regime, where pattern shape highly depends on the z position. It is worth noting, that the correlation values do not decrease to zero due to the fact, that we record a circular random speckle pattern on a square image. The presence of zero values padding the speckles, which are common for all images, lead to the minimum values of 0.25.

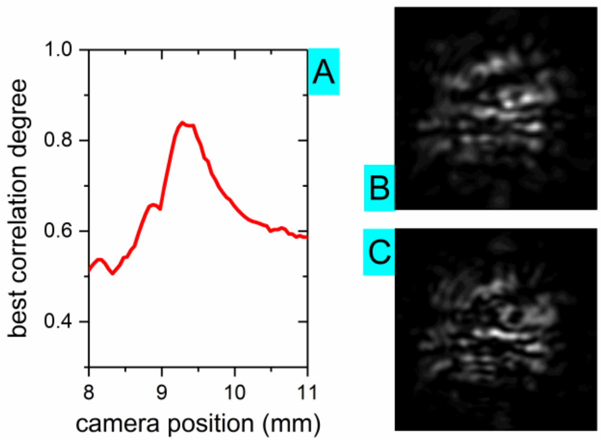

Fig. 3. A) The best obtainable degree of correlation between a speckle pattern acquired in the "reference" FP (lens f=20 cm) and a series of speckle patterns close to the "sample" FP (lens f=15 cm). B-C) An example of reference speckles (B) and sample speckles (C) featuring the best mutual correlation..

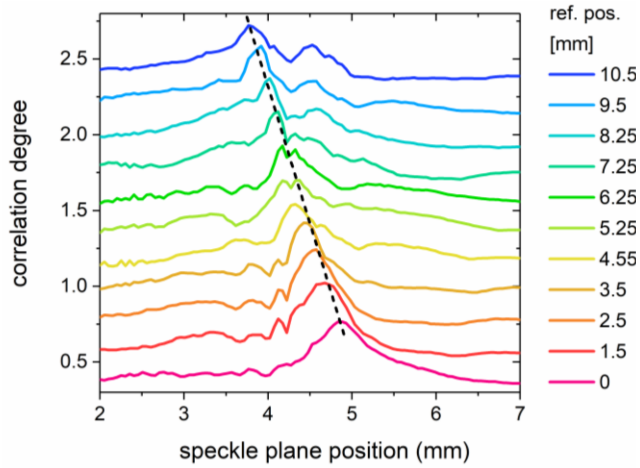

Fig. 4. Comparison of the best obtainable correlation degree between "reference" speckle patterns acquired for various positions (different lines) and "sample" speckle patterns acquired by scanning sample camera along z-axis across sample FP. Dashed line serves as a guide for eye to connect points with the highest degree of correlation.

In the focal plane regime, the speckle patterns along the z-axis are highly uncorrelated. Range of the z-positions, where the FP behavior can be observed is proportional to the Rayleigh range of the lens.

The second important problem consists in the possibility to use a reference FP speckle pattern to characterize the downscaled FP sample pattern. Therefore, we captured a reference image close to the reference FP and a series of sample images with various z-positions. Analogously to the previous case, all images were analyzed and downscaled for the same pattern size. Rotation of cameras was precisely determined based on a testing signal. In order to avoid possible misleading results due to the scaling of the reference pattern, the image scaling was fitted in a preset range of values to acquire the best possible correlation between two patterns.

We obtain a seemingly high degree of correlation for entire range of patterns. This is caused by the fact, that the algorithm is rescaling images to overlap the background parts of images. However, the correlation degree is clearly peaking at the sample FP and comparison of the reference and sample patterns shows a high similarity (up to 0.85 correlation degree).

By comparing the two best matching patterns (see Fig. 3B-C) we observe minor differences in the speckle structure, whereas the general speckle shape remains identical. In other words, we obtain a good agreement for the low spatial frequencies of Fourier transform, unlike for the case of the high spatial frequencies. This effect can be well explained by the fact that low spatial frequencies in FP correspond via Fourier transform to the intensities close to the lens axis, thus meeting well the requirements of the paraxial approximation. High spatial frequencies represent the opposite case.

This behavior has implications for the possible use of FP speckle patterns in SPC technique, as we demonstrate later in the article. We expect the scene low spatial frequencies to be reasonably well reconstructed, whereas the mismatch in the high spatial frequencies will result to an additional noise source in the total intensity measurement.

Finally, we aimed at studying degree of correlation in positions close to reference FP and sample FP. This interest was triggered by the fact that for a range of z-positions close to the FP we obtained patterns, which are not correlated with each other. Therefore, we repeated the experiment presented in Fig. 3 for several positions of the reference camera along the reference FP. We used here two lenses with largely different focal lengths (f_{ref}=20 cm, f_{sam}=2 cm). We acquired a series of reference images and tested correlation with the sample plane images.

In accordance with our expectations, we see a clear shift of the correlation peak, i.e. the shift of camera from the reference FP results in obtaining a correlation with a shifted image in the sample FP. Since the Rayleigh range of the beam is proportional to the lens focal length, we can also observe that the shift in the reference a sample focal planes follow the ratio between focal lengths of the reference a sample lenses, i.e. 1/10. It is worth noting that the curves in Fig. 4 and the sample-reference correlation curves in general feature outside of the focal plane a double-peak structure, which can cause artefacts in the future applications.

V. Imaging And Other Potential Applications

The presented results imply, that it is possible to obtain a random speckle pattern on the scale of tens of micrometers and, at the same time, to acquire a reference image with a high degree of correlation. The reference pattern can be, moreover, significantly scaled up. Such properties can be used in various applications. For instance, our follow-up experiments indicate that the approach can be used for SPC microscopy, where the speckle images serve as random patterns for the scene encoding.

We used an approach analogous to our previously published speckle-based single-pixel hyperspectral camera. [5] We refer reader to the article for more details. Briefly, experimental setup was analogous to the scheme in Fig. 1,

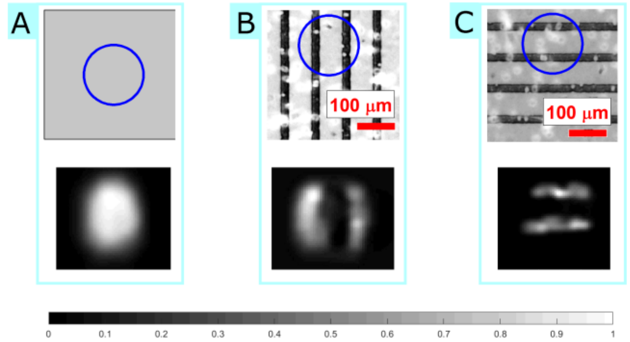

Fig. 5. Examples of original scenes (upper panels) and their reconstructios (lower panels) obtained via hyperspectral imaging using single-pixel camera based on focal-plane speckles. A) White paper, B,C) Screen printed stripes in vertical and horizontal directions. Note that the circular specke pattern delimits the field of view (blue circle in upper panels).

where the sample camera was replaced by a measured sample and the scattered light from the sample was collected by an optical fiber and analyzed by using a spectrometer (Ocean Optics, Flame). The spectrometer served here as the single-pixel detector.

By moving the diffuser (see Fig. 1) we obtained a series of random speckle patterns and for each pattern we measured the total intensities of the scattered laser light. This information is sufficient to computationally reconstruct images of simple testing samples, which were: (i) white surface, (ii) screen printed vertical stripes, and (iii) screen printed horizontal stripes. Resulting reconstructed images (lower panels) compared to the original sample (upper panels) are depicted in Fig. 5.

A limited degree of correlation between sample and reference introduces a new source of noise into the measurement, which decreases quality of the reconstructed images in Fig. 5. Nevertheless, owing to the scaling between reference and sample image, the demonstrated imaging enables us to reach very high spatial resolution while using a low-resolution camera and simple optics, which can be promising in the IR spectral region.

Moreover, unlike in the case of the far-field speckles, the acquired image will be also z-scale dependent. The results presented in Fig. 5 were acquired by using thin planar samples. Since speckle patterns are uncorrelated for different planes outside of the FP, the other image planes cannot be well reconstructed. This fact might lead to artefacts in imaging of a partly transparent sample, where various z-planes of the scene induce different modulations, which finally sum up in the total intensity.

On the other hand, this feature can be employed in speckle-based imaging featuring resolution in all x, y, and z-direction. Here the limiting factor will be, among other facts, the double-peak structure of correlation curves in Fig. 4. Our future work will closely address this direction.

At the same time, we can think of the FP pattern correlation as a form of random interferometry. Instead of observing a usual regular interferogram of plane waves we observe an interferogram of many random waves producing unique pattern for each position. Correlation between sample and reference images makes it possible to tune precisely relative positions of the two image planes. Moreover, by tuning relative strength of focusing length we can tune also the “gear” factor between the two branches. Analogously to the previous case, the double-peak character of sample-reference correlation curves can lead to artefacts which will be addressed in our future work.

VI. Conclusions

We presented a study on properties of refocused far-field speckle patterns close to the focal plane of a lens. At the same time, we have demonstrated that such speckle patterns can be used for compressive imaging.

We studied a region in the focal plane proximity, which corresponds to the speckle beam Rayleigh range, where the speckle pattern shape highly depends on the exact plane position. The speckle patterns are therefore mutually uncorrelated. We prove that the focal-plane speckle patterns can be referenced by splitting the beams into two paths by using a different lens. This opens the possibility to manipulate with scaling between the original and reference pattern.

The reference pattern follows the misplacement of the original one from the exact focal plane. This can be potentially employed in the compressive imaging to introduce three-dimensional slicing of a scene, but it can also serve as a means to precisely determine position of the pattern.

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