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Shaping the amplitude and phase of laser beams by using a phase-only spatial light modulator

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Corresponding Author:	Omel Mendoza-Yero SPAIN
Corresponding Author's Institution:	
Corresponding Author E-Mail:	omendoza@fca.uji.es
Order of Authors:	Omel Mendoza-Yero
	Miguel Carbonell-Leal
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In this video-contribution we describe in details a protocol for encoding the amplitude and phase of laser beams by using a phase-only spatial light modulator. The corresponding complex field is retrieved at the output plane of an imaging optical system after the spatial filtering of all frequency components of the light but the zero one. The lack from random or diffuser elements within the optical setup allows obtaining amplitude and phase patterns without coherent noise. The encoding protocol is based on a direct codification algorithm, whereas all light management is performed on-axis. In addition, arbitrary and independent amplitude and phase modulation can be dynamically carried out at the frequency refresh time of the spatial light modulator. We believe that this encoding protocol can be employed for shaping the amplitude and phase of laser beams in several applications that range from material micro-processing to linear and nonlinear microscopy.

TITLE:
Shaping the Amplitude and Phase of Laser Beams by Using a Phase-Only Spatial Light Modulator

AUTHORS AND AFFILIATIONS:
Miguel Carbonell-Leal[1], and Omel Mendoza-Yero[1]
[1]Institut de Noves Tecnologies de la Imatge (INIT), Universitat Jaume I, Castelló, Spain

Corresponding Author:
Omel Mendoza-Yero (omendoza@uji.es)

Email Addresses of Co-author:
Miguel Carbonell-Leal (carbonem@uji.es)

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SUMMARY:
We show how to encode the complex field of laser beams by using a single phase element. A common-path interferometer is employed to mix the phase information displayed into a phase-only spatial light modulator to finally retrieve the desired complex field pattern at the output of an optical imaging system.

ABSTRACT:
The aim of this article is to visually demonstrate the utilization of an interferometric method for encoding complex fields associated with coherent laser radiation. The method is based on the coherent sum of two uniform waves, previously encoded into a phase-only spatial light modulator (SLM) by spatial multiplexing of their phases. Here, the interference process is carried out by spatial filtering of light frequencies at the Fourier plane of certain imaging system. The correct implementation of this method allows arbitrary phase and amplitude information to be retrieved at the output of the optical system.

It is an on-axis, rather than off-axis encoding technique, with a direct processing algorithm (not an iterative loop), and free from coherent noise (speckle). The complex field can be **exactly retrieved** at the output of the optical system, except for some loss of resolution due to the frequency filtering process. The main limitation of the method might come from the inability to operate at frequency rates higher than the refresh rate of the SLM. Applications include, but are not limited to, linear and non-linear microscopy, beam shaping, or laser micro-processing of material surfaces.

INTRODUCTION:
Almost all laser applications are in close relation with the management of the optical wavefront of light. In the paraxial approximation, the complex field associated with the laser radiation can be described by two terms, the amplitude and the phase. Having control over these two terms is

necessary to modify both the temporal and the spatial structure of laser beams at will. In general, the amplitude and the phase of a laser beam can be properly changed by several methods including the use of optical components that range from single bulk lenses, beam splitters and mirrors to most complex devices like deformable mirrors or spatial light modulators. Here, we show a method for encoding and reconstructing the complex field of coherent laser beams, which is based on dual-phase hologram theory[1], and the utilization of a common-path interferometer.

Nowadays, there exists a wide variety of methods to encode the complex fields of laser beams[2-5]. In this context, some well-established methods to produce phase and amplitude modulation rely on the use of digital holograms[6]. A common point in all these methods is the necessity of generating a spatial offset to separate the desired output beam from the zeroth-order coming from the reflection of light at the SLM display. These methods are basically off-axis (usually applying for the first diffraction order of the grating), employing phase grating not only to encode the phase, but also to introduce necessary amplitude modulation. In particular, amplitude modulation is performed by spatially lowering the grating height, which clearly degrades the diffraction efficiency. The hologram reconstruction process mostly gets an approximate, but not exact, reconstruction of the amplitude and phase of the desired complex field. Discrepancies between theory and experiment seem to appear from an inaccurate encoding of the amplitude information as well as other experimental issues happening during the spatial filtering of the first diffraction order or due to SLM pixilation effects. In addition, the intensity profile of the input beam can introduce restrictions on the output power.

In contrast, with the introduced method[7], all light management is carried out on-axis, which is very convenient from an experimental point of view. Additionally, it takes advantage of considering, in the paraxial approximation, the complex field associated with laser beams as a sum of two uniform waves. The amplitude information is synthetized by the interference of these uniform waves. In practice, such interference is carried out by spatial filtering of light frequencies at the Fourier plane of a given imaging system. Previously, the phase patterns associated with the uniform waves are spatially multiplexed and encoded into a phase-only SLM (placed at the entrance plane of this imaging system). Hence, the whole optical setup can be regarded as a common-path interferometer (very robust against mechanical vibrations, temperature changes, or optical misalignments). Please, note that the abovementioned interference process can be alternatively accomplished by using other optical layouts: with a couple of phase-only SLMs properly placed within a typical two-arm interferometer, or by time sequentially encoding the two phase patterns into the SLM (previous introduction of a reference mirror in the optical setup). In both cases, there is no necessity of spatial filtering, and consequently no loss of spatial resolution, at the expense of increasing the complexity of the optical system, as well as the alignment process. Here, it should be also emphasized that by using this encoding method, the full spectrum of the desired complex field can be **exactly retrieved** at the Fourier plane, after filtering all diffraction orders but the zeroth one.

On the other hand, the efficiency of the method depends on several factors: the manufacturer's specifications of the SLM (e.g., fill factor, reflectivity, or diffraction efficiency), the size of the encoded pattern, and the way at which the light impinges onto the SLM (reflection with a small hitting angle, or normal incidence by using a beam splitter). At this point, under proper experimental conditions, the measured total light efficiency can be more than 30%. However, note that that the total light efficiency just due to the use of the SLM can be less than 50%. The lack of random or diffuser elements within the optical setup allows the retrieving of amplitude and phase patterns without coherent noise (speckle). Other significant aspects to point out are the utilization of a direct codification algorithm rather than iterative procedures and its ability to perform arbitrary and independent amplitude and phase modulation at the frequency refresh time of the SLM (up to hundreds of hertz according to the current technology).

In principle, the method[7] is intended to be used with input plane waves, but it is not limited to that. For instance, if a Gaussian beam is hitting the SLM, it is possible to modify its irradiance shape at the output of the system by encoding a suited amplitude pattern into the SLM. However, as the intensity of the output beam cannot exceed that of the input beam at any transversal position (x,y), the shaping of the amplitude is performed by intensity losses originated by a partially destructive interference process.

The theory underlining the encoding method[7] is as follows. Any complex field represented in the form $U(x,y) = A(x,y)e^{i\varphi(x,y)}$ can be also rewritten as:

$$U(x,y) = Be^{i\theta(x,y)} + Be^{i\vartheta(x,y)} \quad (1)$$

where

$$\theta(x,y) = \varphi(x,y) + \cos^{-1}[A(x,y)/A_{\max}] \quad (2)$$

$$\vartheta(x,y) = \varphi(x,y) - \cos^{-1}[A(x,y)/A_{\max}] \quad (3)$$

In equations 1-3, the amplitude and phase of the two-dimensional complex field $U(x,y)$ is given by $A(x,y)$ and $\varphi(x,y)$, respectively. Note that, terms A_{max} (maximum of $A(x,y)$) and $B = A_{max}/2$ do not depend on the transversal coordinates (x,y). From the theory, if we set $A_{max} = 2$, then $B = 1$. Hence, the complex field $U(x,y)$ can be obtained, in a simple manner, from the coherent sum of uniform waves $Be^{i\theta(x,y)}$ and $Be^{i\vartheta(x,y)}$. In practice, this is accomplished with a common-path interferometer made up of a single phase element $\alpha(x,y)$, placed at the input plane of an imaging system. The single phase element is constructed by spatial multiplexing of the phase terms $\theta(x,y)$ and $\vartheta(x,y)$ with the help of two-dimensional binary gratings (checkerboard patterns) $M_1(x,y)$ and $M_2(x,y)$ as follows

$$M_1(x,y)e^{i\theta(x,y)} + M_2(x,y)e^{i\vartheta(x,y)} = e^{i\alpha(x,y)} \quad (4)$$

hence,

$$\alpha(x,y) = M_1(x,y)\theta(x,y) + M_2(x,y)\vartheta(x,y) \quad (5)$$

These binary patterns fulfill the condition $M_1(x,y) + M_2(x,y) = 1$. Note that, the interference of uniform waves cannot happen if we do not mix the information contained in the phase element $\alpha(x,y)$. In the present method, this is carried out by using a spatial filter able to block all diffraction orders but the zeroth one. In this way, after the filtering process at the Fourier plane, the spectrum $H(u,v) = F\{e^{i\alpha(x,y)}\}$ of the encoded phase function is related to the spectrum of the complex field $F\{U(x,y)\}$ by the expression

$$H(u,v)P(u,v) = \frac{F\{U(x,y)\}}{2} \quad (6)$$

In Eq. (6), (u,v) denote coordinates in the frequency domain, $P(u,v)$ holds for the spatial filter, whereas the Fourier transform of a given function $\Theta(x,y)$ is represented in the form $F\{\Theta(x,y)\}$. From Eq. (6), it follows that, at the output plane of the imaging system, the retrieved complex field $U_{RET}(x,y)$, (without considering constant factors), is given by the convolution of the magnified and spatially reversed complex field $U(x,y)$ with the Fourier transform of the filter mask. That is:

$$U_{RET}(x,y) = U(-x/Mag, -y/Mag) \otimes F\{P(u,v)\} \qquad (7)$$

In Eq. (7), the convolution operation is denoted by the symbol ⊗, and the term *Mag* represents the magnification of the imaging system. Hence, the amplitude and phase of $U(x,y)$ is fully retrieved at the output plane, except for some loss of spatial resolution due to the convolution operation.

PROTOCOL:

1. Encoding the Complex Field into a Single Phase Element

1.1. From the technical specifications of the SLM, find its spatial resolution (for instance 1920 pixels x 1800 pixels).

1.2. Define and generate the desired amplitude $A(x,y)$ and phase $\varphi(x,y)$ patterns as digital images.

1.2.1. Set the spatial resolution of abovementioned digital images equal to that of the SLM display.

1.2.2. Set abovementioned digital images in gray level format.

1.2.3. Set the minimum and maximum values of the amplitude and phase images from 0 to 255, and from -π/2 to π/2, respectively.

1.2.4. Set A_{max} = 2 in equations 2 and 3, and computer-generate the phase patterns $\theta(x,y)$ and $\vartheta(x,y)$ from them.

1.3. Computer generate the checkerboard patterns $M_1(x,y)$ and $M_2(x,y)$.

1.3.1. Set the spatial resolution of these checkerboard patterns equal to that of the SLM display.

1.3.2. To reduce the effect of pixel crosstalk, generate other pairs of checkerboard patterns $M_1(x,y)$ and $M_2(x,y)$ constructed with different pixel cells having an increased number of pixels (for instance: 2x2, 3x3, and 4x4 pixel cells, *etc.*).

CAUTION: When increasing the pixel cell, the total number of pixels of checkerboard patterns must be kept unchanged and equal to the spatial resolution of the SLM. Ensure that final number of pixels of all checkerboard patterns remains the same after modifying their pixel cells.

1.4. Computer generate the single phase element $\alpha(x,y)$ from equation 5.

NOTE: See supplemental material named “MATLAB_code_1.m” for related tasks on step 1 of this protocol.

2. Reconstruction of the Complex Field

2.1. Use a collimated, linear polarized, and spatially coherent laser beam as a light source.

2.2. Use a phase-only SLM with at least 2π phase range.

2.3. When necessary, use a proper beam expander to adjust the size of the beam to the size of the SLM display.

2.4. When necessary, use an optical polarizer to set laser beam polarization to the horizontal direction. This is usually important for the proper operation of phase-only SLMs, which are typically designed to modulate the spatial phase of the electromagnetic field that oscillate in the horizontal direction, keeping unchanged its vertical components.

2.5. In order to send a phase pattern to the SLM, follow standard communication protocols given by the SLM’s manufacturer to connect and control the SLM with the computer.

NOTE: Common protocol for this purpose includes the use of a calibration curve to transform the values in radians (due to mathematical operations with angles) into gray level ones, which the electronic control unit of the SLM will finally convert into voltage levels. Additionally, as the SLM is connected to computer as an external device with its own screen, an extension of the computer screen is usually necessary, as well as a proper program to send the corresponding gray level images to this extra screen. An example of these codes is also included as supplemental material (please, see MATLAB_code_2.m).

2.6. Implement an image optical system and put the display of the SLM in the input plane of this system.

2.6.1. Use a refractive lens of a focal length f to construct a 2f x 2f optical image system (a 4f optical system is also valid for this task). In accordance with the expected output size of the complex field, beam width, wavelength of light, and the available physical space, employ lens/lenses with suited technical specifications (e.g., coating, size, focal length, *etc.*).

2.6.2. To find the position of the output plane of the imaging system, send the phase pattern $\alpha(x,y)$ to the SLM and visually look for the recorded image (depending on the position of the camera) with the best spatial resolution.

CAUTION: In the case of low-size pixel cells (for instance, 1x1 pixel cells) and SLM displays with pixel widths of a few microns (for instance, 8 µm), only beam propagation can produce interference between encoded uniform waves, getting a reconstructed images without including the circular iris in the imaging system. Use low-size pixel cells to locate the position of the output plane.

2.6.3. Place a circular iris of variable diameter at the Fourier plane of the optical system and align its center with that of the laser beam focus.

2.6.4. To adjust the size of the circular iris at the Fourier plane, send the phase pattern $\alpha(x,y)$ and visually look for the recorded image (depending on the diameter of the circular iris) with best spatial resolution.

CAUTION: In the case of long-size pixel cells (for instance, 4x4 pixel cells), the interference between encoded uniform waves is basically carried out with the spatial filter. Use long-size pixel cell to adjust the size of the circular iris. In this protocol, the terms low-size and long-size are referred to the number of pixels contained within a pixel cell. However, the abovementioned interference depends also on the pixel width. Employ SLMs with pixel widths equal or less than 8 µm.

2.7. Send the gray level image corresponding to the phase element $\alpha(x,y)$ to the SLM.

2.7.1. To minimize the crosstalk effect, look for the best pixel cell size which allow achieving the recorded image with the higher spatial resolution.

3. Measure the Reconstructed Complex Field

3.1 Implement the polarization-based phase shifting technique[8].

3.1.1. Place and align the rotation angle of the first optical polarizer, located just before the SLM (see **Figure 2**). To set the rotation angle of the first polarizer, visually look for the maximum and minimal light transmittance in the CCD camera (placed at the output plane of the imaging system), depending on the rotation of the polarizer. Write down the two corresponding angles of the polarizer. Fix the final angle of the polarizer to that between the two previous-recorded angles.

3.1.2. Place and align the rotation angle of the second optical polarizer, located after the Fourier plane of the imaging system (see **Figure 2**). To set the rotation angle of the second polarizer, visually look for the sharpest and most blurred images in the CCD camera (placed at the output plane of the imaging system) after sending the phase pattern $\alpha(x,y)$ to the SLM. Write down the two corresponding angles of the polarizer. Fix the final angle of the second polarizer to that between the previous-recorded angles.

3.2. Record the interferograms.

3.2.1. Keep the CCD camera at the output plane of the imaging system.

3.2.2. To record the first interferogram, add a matrix of 0 radians to the phase element $\alpha(x,y)$ and send it to the SLM. Record corresponding image $I_1(x,y)$ with the CCD.

3.2.3. To record the second interferogram, add a matrix of π/2 radians to the phase element $\alpha(x,y)$ and send it to the SLM. Record corresponding image $I_2(x,y)$ with the CCD camera.

3.2.4. To record the third interferogram, add a matrix of π radians to the phase element $\alpha(x,y)$ and send it to the SLM. Record corresponding image $I_3(x,y)$ with the CCD camera.

3.2.5. To record the fourth and last interferogram, add a matrix of 3π/2 radians to the phase element $\alpha(x,y)$ and send it to the SLM. Record corresponding image $I_4(x,y)$ with the CCD camera.

3.3. Reconstruct the complex field.

NOTE: See supplemental material named “MATLAB_code_3.m” for related tasks on this point of the protocol.

3.3.1. Retrieve the amplitude of the complex field $A_{retrieved}(x,y)$ by using the expression

$$A_{retrieved}(x,y) = \sqrt{[I_3(x,y) - I_1(x,y)]^2 + [I_4(x,y) - I_2(x,y)]^2} \tag{8}$$

3.3.2. Retrieve the phase of the complex field $\varphi_{retrieved}(x,y)$ by using the expression

$$\varphi_{retrieved}(x,y) = \arctan\left[\frac{I_4(x,y) - I_2(x,y)}{I_3(x,y) - I_1(x,y)}\right] \tag{9}$$

3.4. To reduce discrepancies between the retrieved phase $\varphi_{retrieved}(x,y)$ and the theoretical phase pattern $\varphi(x,y)$, pre-compensate possible phase aberrations at the SLM plane.

3.4.1. Encode only the flat phase pattern $\varphi_0 = 0$ into the SLM, and then retrieve the phase $\varphi_{laser}(x,y)$ of the laser beam at the SLM after implanting again the above-described polarization-based phase shifting technique.

3.4.2. In step 1.2 of the protocol, add $-\varphi_{laser}(x,y)$ to the initial phase pattern $\varphi(x,y)$.

3.4.3. Repeat the remaining steps of the protocol and corroborate that now the spatial shape of $\varphi_{retrieved}(x,y)$ is closer to that of $\varphi(x,y)$ than before.

REPRESENTATIVE RESULTS:

The spatial resolution of the employed phase-only SLM is 1920 pixels x 1080 pixels, with a pixel pitch of 8 µm. The selected amplitude $A(x,y)$ and phase $\varphi(x,y)$ of the complex field are defined by two different gray level images corresponding to the well-known Lenna’s picture (amplitude pattern) and a young girl sticking out her tongue (phase pattern), respectively. In general, for both, the generation of necessary patterns, and the control of the SLM, Matlab codes are utilized. The spatial resolution of these images is set to be 1920 pixels x 1080 pixels. Then, equations 2 and 3 are used to determine the phase patterns $\theta(x,y)$ and $\vartheta(x,y)$ for $A_{max} = 2$. Note that, the numerical value given to A_{max} guaranties that term $B = 1$ and consequently, the complex field

$U(x,y)$ described by Eq. (1) can be understood as the sum of two uniform waves in the simplest form $U(x,y) = e^{i\theta(x,y)} + e^{i\vartheta(x,y)}$. Now, different pairs of binary checkerboard patterns $M_1(x,y)$ and $M_2(x,y)$ (for increased pixel cell sizes), but equal spatial resolution (1920 pixels x 1080 pixels), are computer generated. Particularly, checkerboard patterns made up of 1x1, 2x2, 3x3 and 4x4 pixel cells are digitally constructed by using a programed Matlab function. All abovementioned patterns $A(x,y)$, $\varphi(x,y)$, $\theta(x,y)$, $\vartheta(x,y)$, $M_1(x,y)$, and $M_2(x,y)$ are shown in parts A, B, C, D, E, and F of **Figure 1**, respectively. In parts E and F, and just to get a better visualization of the structure of checkerboard patterns, the constituent pixel cells are of 240 pixels x 240 pixels. From Eq. 5, a set of phase elements $\alpha(x,y)$ for each pair of previously-designed checkerboard patterns are digitally constructed.

[Place **Figure 1** here]

At this point, the expected complex field $U(x,y)$ can be experimentally retrieved at the output plane of an imaging system, once the phase element $\alpha(x,y)$ is sent to the phase-only SLM and the interference between encoded uniform waves takes place. To perform this interference, a spatial filter (for instance, a circular iris) is adjusted in size to block all frequencies but the zeroth one at the Fourier plane of the imaging system (**Figure 2**).

[Place **Figure 2** here]

As a light source, a Ti: Sapphire laser oscillator (working out of the mode locked condition to emit a quasi-monochromatic laser radiation of about 10 nm intensity full width at half maximum (FWHM) and centered at 800 nm) is employed. In addition, to fill almost all the active area of the SLM display (8.64 cm x 15.36 cm) with the laser beam, a commercial 5x telescope beam expander is used. The laser beam is sent (in normal incident) to the display of the SLM by means of a pellicle beam splitter. A refractive lens of focal length 100 mm is placed 200 mm after the SLM and aligned with respect to the optical axis of the laser beam reflected back from the SLM. To locate the position of the output plane of the imaging system, the image of $A(x,y)$ recorded the CCD camera was found. This is done once the phase element $\alpha(x,y)$ (formed with 1x1 pixel cells) is sent to the SLM. Then, a circular iris is placed at the Fourier plane of the optical system, and aligned with respect to the focus of the laser beam. In addition, to adjust the size of the circular iris, its diameter is varied until better image reconstruction is achieved by visual inspection in the CCD camera. To this purpose, the phase element $\alpha(x,y)$ (digitally constructed with 4x4 pixel cells) was previously sent to the SLM. To minimize the effect of pixel crosstalk, the best phase element $\alpha(x,y)$ (depending on the pixel cell size) that allows achieving the image with higher spatial resolution in the CCD is found.

In order to corroborate that the desired complex field is reconstructed at the output plane of the imaging system, the already-mentioned polarization-based phase shifting technique is used to measure its amplitude and phase. To do that, a couple of polarizers p (one placed before the SLM, and another after the output plane of the imaging system) are properly aligned within the optical setup (see **Figure 2**), following the procedure described in steps 3.1.2 and 3.1.4 of the protocol. Then, the interferograms associated with the four-step phase shifting technique $I_1(x,y)$,

$I_2(x,y)$, $I_3(x,y)$, and $I_4(x,y)$ are recorded with the CCD camera (already placed at the output plane of the imaging system). Here, it should be recalled that these four interferograms are recorded with the camera after the addition of 0, $\pi/2$, π, and $3\pi/2$ to the phase element $\alpha(x,y)$ (see steps 3.2.2 - 3.2.5 of the protocol for details). Finally, using equations 8 and 9, the amplitude and phase of the reconstructed complex field can be retrieved. For this experiment, the results are shown in **Figure 3**.

[Place **Figure 3** here]

FIGURE AND TABLE LEGENDS:

Figure 1: Computer generated patterns associated with the introduced encoding method. (**A**) User-defined amplitude pattern of the complex field. (**B**) User-defined phase pattern of the complex field. (**C**) Phase pattern corresponding to the first uniform wave in equation 1. (**D**) Phase pattern corresponding to the second uniform wave in equation 1. (**E**) First checkerboard pattern following the sampling process described with equation 4. (**F**) Second checkerboard pattern following the sampling process described with equation 4.

Figure 2: Optical setup used to accomplish the encoding method. Imaging system composed of a spatial light modulator (SLM), beam splitter (BS), and single refractive lens (L) of focal length 200 mm. In the Fourier plane is included a hard iris, which is employed as a spatial filter (SF) to block all frequencies but the zero one. In addition, at the output plane of the imaging system is placed a camera (CCD) to record amplitude patterns, and interferograms. Only to measure the generated complex field by means of polarization-based phase shifting technique, a couple of optical polarizers (P) are properly located within the optical setup.

Figure 3: Representative experimental results under quasi-monochromatic illumination. (**A**) User-defined amplitude pattern of the complex field. (**B**) User-defined phase pattern of the complex field. (**C**) Interferograms associated with the polarization-based phase shifting technique developed in four steps and obtained after adding 0, $\pi/2$, π, and $3\pi/2$ to the phase element $\alpha(x,y)$. (**D**) Retrieved experimental amplitude pattern. (**E**) Retrieved experimental phase pattern.

Figure 4: Representative experimental results under ultrashort pulsed illumination. (**A**) User-defined amplitude pattern of the complex field. (**B**) User-defined phase pattern of the complex field. (**C**) Interferograms associated with the polarization-based phase shifting technique developed in four steps and obtained after adding 0, $\pi/2$, π, and $3\pi/2$ to the phase element $\alpha(x,y)$. (**D**) Retrieved experimental amplitude pattern. (**E**) Retrieved experimental phase pattern.

DISCUSSION:

In this protocol, practical parameters as the pixel width of the phase-only SLM or the number of pixels contained within pixel cells of a computer-generated pattern are key points to successfully implement the encoding method. In steps 1.2, 1.3, and 1.4 of the protocol, the shorter the pixel width, the better the spatial resolution of the retrieved amplitude and phase patterns. In addition, as the codification into the SLM of abrupt pixel-to-pixel phase modulations can originate unexpected phase responses (pixel crosstalk), the construction of checkerboard patterns (as described in step 1.4) should be linked to the increment of the number of pixels within pixel cells. The main reason to do that is to mitigate the effects of pixel crosstalk on the retrieved amplitude and phase patterns. However, when increasing the number of pixels within the pixel cells, the spatial resolution of the recorded complex field patterns $A_{retrieved}(x,y)$ and $\varphi_{retrieved}(x,y)$ is decreased. Hence, having high spatial resolution SLMs with low pixel widths allows reducing possible crosstalk effects, without losing significant spatial resolution in the retrieved amplitude and phase patterns.

Furthermore, in step 1.2.3 of the protocol, the phase of the complex field is defined from - π/2 to π/2. The main reason for setting such phase range is to generate a phase element $\alpha(x,y)$ ranging from -π to π, which can be implemented into a SLM with 2π of phase range. However, if the phase range of the available SLM is greater than 2π, the phase of the complex field could be defined within an extended range (for instance: for $\varphi(x,y)$ ranging from -π to π, the phase element $\alpha(x,y)$ may range from -3π/2 to 3π/2, and consequently the phase range of the SLM must be, at least, 3π).

The characteristics of the laser beam could also influence the results of the encoding method. Pay special attention to the steps 2.1-2.3, setting the right polarization direction, collimation, and transversal size of the laser beam before following the remaining steps of the protocol. Furthermore, as phase-only SLMs are basically diffractive-dependent optical devices based on the interference phenomenon, it is necessary to use laser beams with high/good spatial coherence.

On the other hand, instead of quasi-monochromatic, ultrashort pulsed illumination also allows obtaining good results. In this case, the different spectral components of the pulse are phase modulated (in a very similar manner) just with the single phase element $\alpha(x,y)$. Here, to show the effect of a broadband light source on the encoding method, we repeat all steps of the protocol, but this time for pulsed radiation (an ultrashort pulse of about 12 fs FWHM, centered at 800 nm, spectral bandwidth of 100 nm FWHM, emitted by a mode-locked Ti:Sapphire laser from the femtolaser, at a 75 MHz repetition rate). The results are shown in **Figure 4**. Note that, due to the mix of the different spectral components of the pulse, the retrieved patterns are very close to the expected ones.

[Place **Figure 4** here]

Laser beams are intrinsically complex fields, so in most potential applications one should be able to modify their amplitude and phase, simultaneously. The present method allows to do that by means of a single phase element (implemented or not into a phase-only SLM). We believe that, in a near future, this method could be employed, for instance in the illumination path of microscopes[9,10] for simultaneous linear and non-linear excitation of different zones of biological samples, or in parallel micro-processing[11,12] of materials. In both applications the role of amplitude modulation is apparent, meanwhile phase modulation can be utilized, at the same time, for compensation of optical aberrations at the sample/processing plane. Finally, it should be mentioned that the encoding method described with the present protocol is not limited to the utilization of SLMs. Fixed phase elements $\alpha(x,y)$ constructed with other techniques (for instance: photolithographic techniques) can be a different, but equally valid option to implement this protocol.

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DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

Figure 3

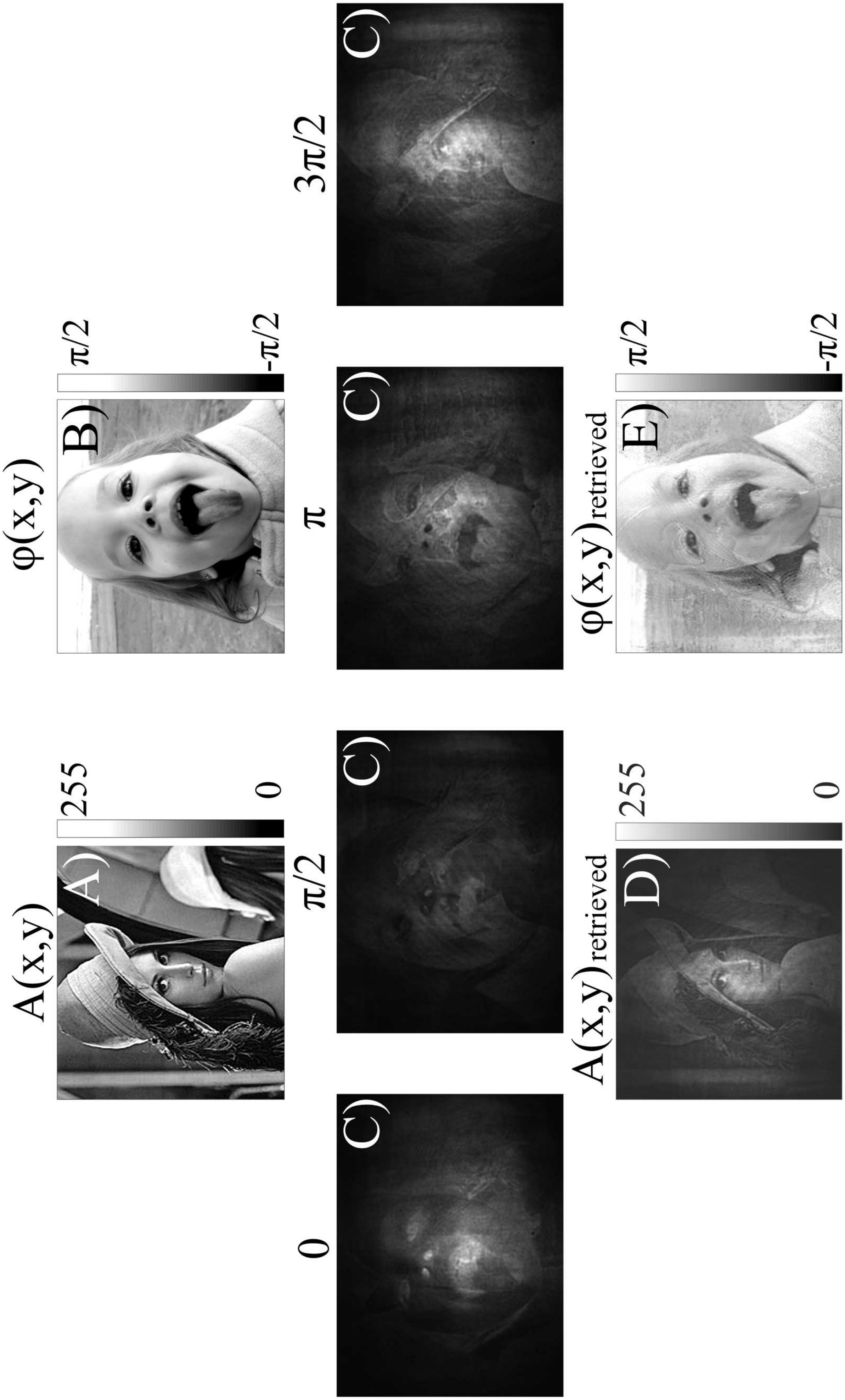
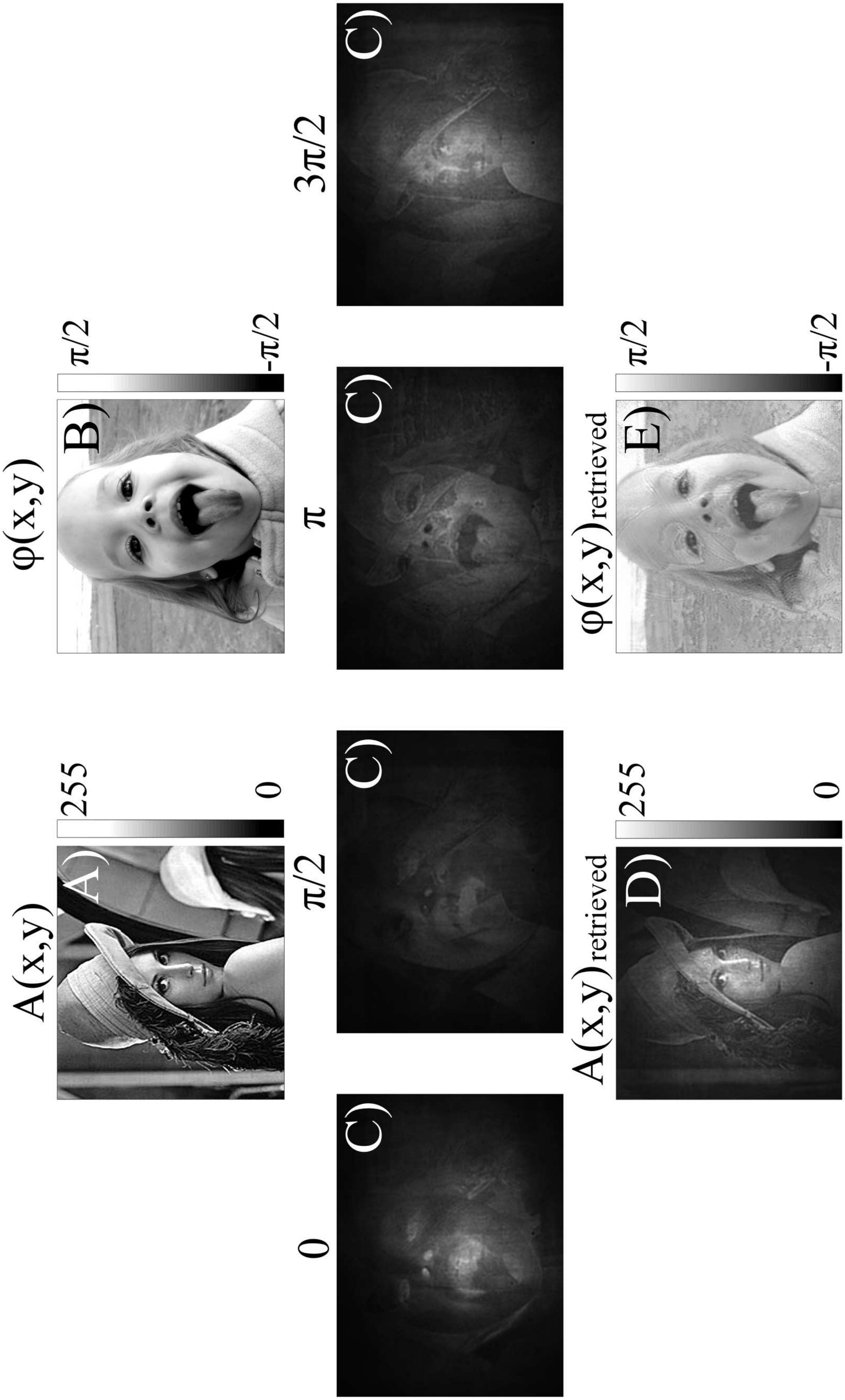
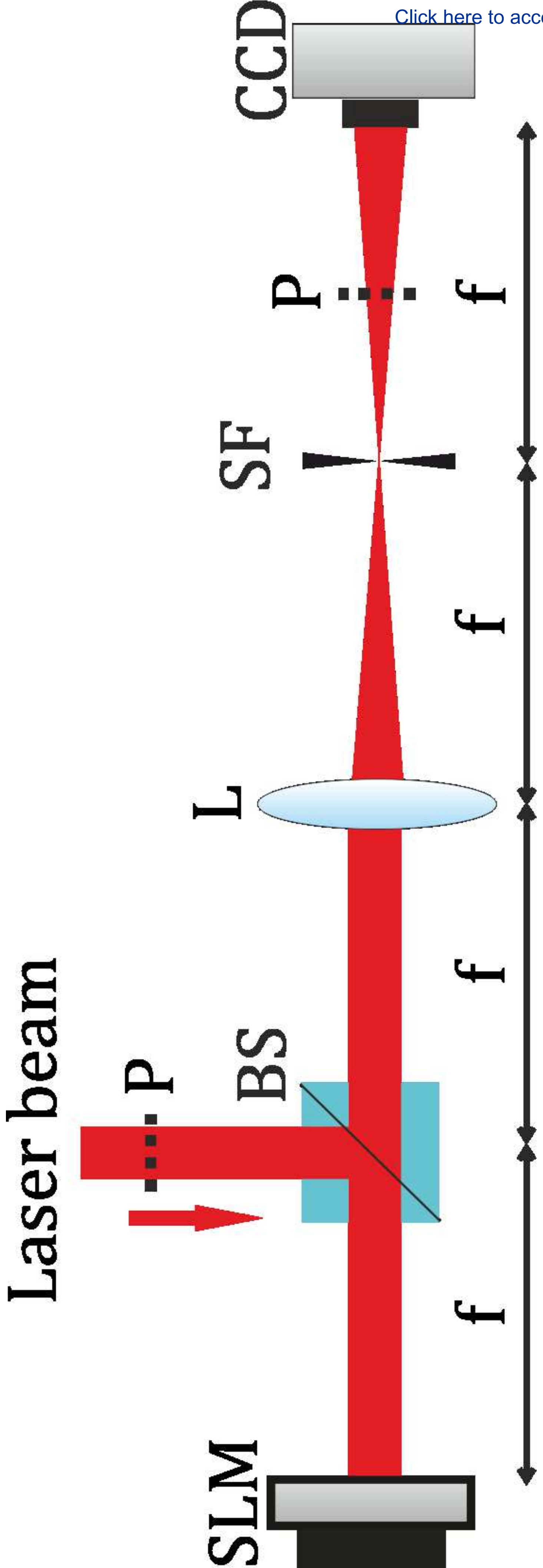

A(x,y)
A)
255
0
φ(x,y)
B)
π/2
-π/2
0
π/2
π
3π/2
C)
A(x,y)retrieved
D)
255
0
φ(x,y)retrieved
E)
π/2
-π/2

Figure 4


A(x,y)
A)
255
0
φ(x,y)
B)
π/2
-π/2
0
π/2
π
3π/2
C)
C)
C)
C)
A(x,y)retrieved
D)
255
0
φ(x,y)retrieved
E)
π/2
-π/2


CCD
P
f
SF
f
L
Laser beam
P
BS
f
f
SLM

MATLAB code 1

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Name of Material/ Equipment	Company	Catalog Number
Achromatic Doublet	THORLABS	AC254-100-B-ML
Achromatic Galilean Beam Expander	THORLABS	GBE05-A
Basler camera	BASLER	avA1600-50gm GigE camera
Mounted Zero-Aperture Iris	THORLABS	ID12Z/M
Pellicle Beamsplitter	THORLABS	CM1-BP145B2
PLUTO Spatial Light Modulator	HOLOEYE Photonics AG	NIR-II
Two thin film laser polarizers	EKSMA OPTICS	420-0526M

Comments/Description

Lens Diameter 25.4 mm, focal length 100 mm

AR Coated: 400 - 650 nm

sensor size 8.8 mm x 6.6 mm, pizel size 5.5 microns

Max Aperture 12 mm

45:55 (R:T), Coating: 700 - 900 nm

Phase Only Spatial Light Modulator (Optimized for 700 -1000 nm)

material BK7, diameter 50 mm, wavelength 780-820 nm

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Institution:	University Jaume I
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Responses to reviewer's comments

Jove manuscript: JoVE59158

Title: Shaping the amplitude and phase of laser beams by using a phase-only spatial light modulator.

Comments of reviewer #1:

Manuscript Summary:

The manuscript presents a method to control the spatial amplitude and phase of a laser beam using a phase-only spatial light modulator. The method for generating such pattern relies on common-path interference resulting from a single phase pattern and the manuscript describes the technique clearly and concisely.

Major Concerns:

I have no major concerns, the work is technically correct and well presented.

Minor Concerns:

The main concern that I would like to see addressed is how this technique compares to the alternatives. In particular it has been typical to achieve amplitude and phase modulation using digital holograms, a selection of methods for producing these can be found in [Opt. Express 24, 6249-6264 (2016).]. This paper is very clear in how I can realise this technique, but as an SLM user, I would like also to know the advantages and disadvantages that this method has over digital holograms. You might talk about the efficiency of your system, which might be greater than the typical 85% found for digital holograms, though this is not clear as you use a pillicle to couple your beam in. In any case, I would like to see a discussion of the advantages and disadvantages of this method. A smaller note, is that you do not mention how to account for the input beam amplitude, if you have for instance a Gaussian beam shape hitting the SLM, then your phase pattern should *change to take this into account to achieve the best possible output beam, have you considered how to account for this?*

Respond to reviewer #1:

We would like to answer minor concerns of reviewer #1 by introducing the following sentences at the introduction section.

In this context, some well-established methods to produce phase and amplitude modulation rely on the use of digital holograms[6]. A common point in all these methods is the necessity of generating a spatial offset to separate the desired output beam from the zeroth-order coming from the reflection of light at the SLM display. So, these methods are basically off-axis (they usually apply for the first diffraction order of the grating), employing phase grating not only to encode the phase, but also to introduce necessary amplitude modulation. In particular, amplitude modulation is performed by spatially lowering the grating height, which clearly degrades the diffraction efficiency. The hologram reconstruction process mostly gets an approximate, but not exact, reconstruction of the amplitude and phase of the desired complex field. Discrepancies between theory and experiment seem to appear from an inaccurate encoding of the amplitude information as well as other experimental issues happening during the spatial filtering of the first diffraction order or due to SLM pixelation effects. In addition, the intensity profile of the input beam can introduce restrictions on the output power.

In contrast, with the introduced method[7] all light management is carried out on-axis, which is very convenient from an experimental point of view. Additionally, it takes advantage of considering, in the paraxial approximation, the complex field associated with laser beams as a sum of two uniform waves. The amplitude information is synthetized by the interference of these uniform waves. In practice, such interference is carried out by spatial filtering of light frequencies at the Fourier plane of a given imaging system. Previously, the phase patterns associated with the uniform waves are spatially multiplexed and encoded into a phase-only SLM (placed at the entrance plane of this imaging system). Hence, the whole optical setup can be regarded as a common-path interferometer (very robust against mechanical vibrations, temperature changes, or optical misalignments). Please, note that the above-mentioned interference process can be alternatively accomplished by using other optical layouts. For instance, with a couple of phase-only SLMs properly placed within a typical two-arm interferometer, or by time sequentially encoding the two phase patterns into the SLM (previous introduction of a reference mirror in the optical setup). In both cases there is not necessity of spatial filtering, and consequently no loss of spatial resolution, at expense of increasing the complexity of the optical system, as well as the alignment process. Here, it should be also emphasized that by using this encoding method, the full spectrum of the desired complex field can be **exactly retrieved** at the Fourier plane, after filtering all diffraction orders but the zero one.

On the other hand, the efficiency of the method depends on several factors, including the manufacturer's specifications of the SLM (for instance: fill factor, reflectivity, or diffraction efficiency), the size of the encoded pattern, and the way at which the light impinges onto the SLM (reflection with a small hitting angle, or normal incidence by using a beam splitter). At this point, under proper experimental conditions, the measured total light efficiency can be more than 30%. Please, take into account that the total light efficiency just due to the use of the SLM can be less than 50%. The lack of random or diffuser elements within the optical setup allows retrieving amplitude and phase patterns without coherent noise (speckle). Other significant aspects to point out are the utilization of a direct codification algorithm rather than iterative procedures, or its ability to perform arbitrary and independent amplitude and phase modulation at the frequency refresh time of the SLM (up to hundreds of Hz according to the current technology).

In principle, the method[7] is intended to be used with input plane waves, but it is not limited to that. For instance, if a Gaussian beam is hitting the SLM, it is possible to modify its irradiance shape at the output of the system by encoding a suited amplitude pattern into the SLM. However, as the intensity of the output beam cannot exceed that of the input beam at any transversal position (x, y), the shaping of the amplitude is performed by intensity losses originated by a partially destructive interference process.

ADDED REFERENCE:

6. W. Clark, T., F. Offer, R., Franke-Arnold, S., S. Arnold, A., and Radwell, N. Comparison of beam generation techniques using a phase only spatial light modulator. Optics Express. **24** (6), 6249-6264 (2016).

7. Mendoza-Yero, O., Mínguez-Vega, G., and Lancis, J. Encoding complex fields by using a phase-only

optical element. Optics Letters. **39** (7), 1740-1743 (2014).

Comments of reviewer #2:

Manuscript Summary:

The manuscript describes how to encode and decode fully complex image data from a phase only SLM onto a video camera. The complex data is detected on the camera and decoded using the well known phase shift interferometry method. The complex data is encoded on two spatially interleaved phase only modulations. By blurring the images together using a low enough bandwidth spatial filter, the two phase patterns interfere to produce the desired amplitude and phase on the camera. There is some nice improvement, specifically cancelling fringes from glass surfaces, by using a quasimonochromatic source. The pulsed light source could be useful for avoiding vibration but it looks light even an LED could be used when vibration effects are controlled.

Major Concerns:

The method is sound, but is it very useful. Since one has a phase shift interferometer (with the inclusion of a reference mirror), the two images could be sensed time sequentially eliminating the spatial filter and still reconstructed digitally. In this case with no loss of resolution. One could even directly record the amplitude and phase on just the phase, time sequentially and decode them with the interferometer. From an educational or tutorial standpoint, the system is very useful. Perhaps these various modifications, pros and cons, could be briefly discussed.

Minor Concerns:

The polarization phase shifter mentioned should be included in the schematic. A little more math should be shown on how the Amplitude and Phase are derived from the two phase functions. Also the conclusions section that describes applications of the system is not very well explained. It would be desirable to provide clearer explanation of the benefits of representing complex fields in this way. Is there an application where a designed complex field at the camera plane provides some value?

Respond to reviewer #2:

Major concerns:

We would like to thanks reviewer #2 for the nice comments addressed to improve the encoding method. From a practical point of view, the use of a single-arm interferometer (very robust against unwanted effects, such as mechanical vibrations, temperature changes, or hard alignment processes at micrometric scale) is the main reason for carrying out the coherent mix of uniform waves by spatial filtering of light frequencies at the Fourier plane. Of course, as you mentioned, the use of a spatial filter causes certain loss of spatial resolution due to the convolution operation. Yes, it is possible to avoid this loss of spatial resolution by time sequentially encoding the two phase functions (corresponding to the uniform waves) into the SLM, but above-mentioned problems related to the utilization of two arm interferometers (because of the inclusion of a reference mirror) should appear.

In order to discuss a little bit this important issue, we have included in the introduction section the following sentences:

…The amplitude information is synthetized by the interference of these uniform waves. In practice, such interference is carried out by spatial filtering of light frequencies at the Fourier plane of a given imaging system. Previously, the phase patterns associated with the uniform waves are spatially multiplexed and encoded into a phase-only SLM (placed at the entrance plane of this imaging system). Hence, the whole optical setup can be regarded as a common-path interferometer (very robust against mechanical vibrations, temperature changes, optical misalignments). Please, note that the above-mentioned interference process can be alternatively accomplished by using other optical layouts. For instance, with a couple of phase-only SLMs properly placed within a typical two-arm interferometer, or by time sequentially encoding the two phase patterns into the SLM (previous introduction of a reference mirror in the optical setup). In both cases there is not necessity of spatial filtering, and consequently no loss of spatial resolution at expense of increasing the complexity of the optical system, as well as the alignment process…

Minor concerns:

In accordance with the reviewer suggestions:

1. Two polarizers are now represented in **Figure 2**. However, please note that in the optical system used for shaping the amplitude and phase of laser beams, polarizers have nothing to do. The function of them is just the measurement of the already generated complex field through the phase shifting technique. That is why, in the first version of **Figure 2**, polarizers had not been placed.
2. We add and/or modify, in the introduction section, the following sentences (together with supported equations) to further clarify how the amplitude and phase are derived from the two phase functions:

Note that, the interference of uniform waves cannot happen if we do not mix the information contained in the phase element $\alpha(x,y)$. In the present method, this is carried out by using a spatial filter able to block all diffraction orders but the zero one. In this way, after the filtering process at the Fourier plane, the spectrum $H(u,v)=F\{e^{i\alpha(x,y)}\}$ of the encoded phase function is related to the spectrum of the complex field $F\{U(x,y)\}$ by the expression

$$H(u,v)P(u,v) = \frac{F\{U(x,y)\}}{2} \tag{6}$$

In Eq. (6), u,v denote coordinates in the frequency domain, $P(u,v)$ holds for the spatial filter, whereas the Fourier transform of a given function $\Theta(x,y)$ is represented in the form $F\{\Theta(x,y)\}$. From Eq. (6), it follows that, at the output plane of the imaging system, the retrieved complex field $U_{RET}(x,y)$, (without considering constant factors), is given by the convolution of the magnified and spatially reversed complex field $U(x,y)$ with the Fourier transform of the filter mask. That is:

$$U_{RET}(x,y) = U(-x/Mag, -y/Mag) \otimes F\{P(u,v)\} \tag{7}$$

In Eq.(7), the convolution operation is denoted by the symbol $\otimes$, and the term Mag represents the magnification of the imaging system. Hence, the amplitude and phase of $U(x,y)$ is fully retrieved at the output plane, except for some loss of spatial resolution due to the convolution operation.

3. We improve, in the discussion section, the description of potential/future applications of the proposed method. Now, it appears like this

…Laser beams are intrinsically complex fields, so in most potential applications one should be able to modify their amplitude and phase, simultaneously. The present method allows to do that by means of a single phase element (implemented or not into a phase-only SLM). We believe that, in a near future, this method could be employed, for instance: in the illumination path of microscopes for simultaneous linear and non-linear excitation of different zones of biological samples, or in parallel micro-processing of materials. In both applications the role of amplitude modulation is apparent, meanwhile phase modulation can be utilized, at the same time, for compensation of optical aberrations at the sample/processing plane.

Finally, we would like to thanks both reviewers for their fruitful comments on the present manuscript. We really think that, the present version of the manuscript has been benefited from their suggestions.

Responses to editorial comments

Manuscript, JoVE59158R1 "Shaping the amplitude and phase of laser beams by using a phase-only spatial light modulator"

Editorial comments:

1. Note that all text written in equation editor will be formatted differently than the rest of the text (including inline text). Is it possible to rewrite at least the inline text in the same font as the rest?

2. 1, 3.3: Is it possible to include sample MATLAB code for these steps? It can be included as supplemental material in your submission.

3. 2 and 3.1-3.2: Please include more detail here, as it will be the bulk of what we film and we need enough detail to make a shooting script. E.g., how exactly is the phase pattern sent to the SLM in 2.5.2? How are polarizers aligned in 3.1.1 and 3.1.2? Also, please explicitly refer to Figure 2 during these steps, especially as it appears some equipment is named differently in the protocol and in the figure.

4. Please include at least 10 references.

Responses to editorial comments:

1. In the present version of the manuscript all text written in equation editor (including inline text) was rewritten with a format equal to the text (Calibri 12).

2. MATLAB code for points 1 and 3.3 of the protocol has been generated and included as supplemental material named "MATLAB_code_1.m" and "MATLAB_code_3.m", respectively.

3. To improve this aspects the following sentences have been added/modified in the protocol section:

2.5. In order to send a phase pattern to the SLM, follow standard communication protocols given by the SLM's manufacturer to connect and control the SLM with the computer. Common protocol for this purpose includes the use of a calibration curve to transform the values in radians (due to mathematical operations with angles) into gray level ones, which the electronic control unit of the SLM will finally convert into voltage levels. Additionally, as SLM is connected to computer as external device with its own screen, an extension of the computer screen is usually necessary, as well as a proper program to send the corresponding gray level images to this extra screen. An example of these codes are also included as supplemental material (please, see MATLAB_code_2.m).

3.1.1. Place and align the rotation angle of the first optical polarizer, located just before the SLM (please, see **Figure 2**). To set the rotation angle of the first polarizer, visually look for the maximum and minimal light transmittance in the CCD camera (placed at the output plane of the imaging system), depending on the rotation of the polarizer. Write down the two corresponding angles of the polarizer. Fix the final angle of the polarizer to that between the two previous-recorded angles.

3.1.2. Place and align the rotation angle of the second optical polarizer, located after the Fourier plane of the imaging system (please, see **Figure 2**). To set the rotation angle of the second polarizer, visually look for the sharpest and most blurred images in the CCD camera (placed at the output plane of the imaging system) after sending the phase pattern $\alpha(x,y)$ to the SLM. Write down the two corresponding angles of the polarizer. Fix the final angle of the second polarizer to that between the previous-recorded angles.

3. The following references were added to the manuscript:

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10. Mendoza-Yero, O., Carbonell-Leal, M., Mínguez-Vega, G., and Lancis, J. Generation of multifocal irradiance patterns by using complex Fresnel holograms. Optics Letters. 43 (5), 1167-1170 (2018).

11. Kuang, Z., Liu, D., Perrie, W., Cheng, J., Shang, S., Edwardson, S. P., Fearon, E., Dearden, G., and Watkins, K. G. Diffractive Multi-beam Ultra-fast Laser Micro-processing Using a Spatial Light Modulator(Invited Paper). Chinese Journal of Lasers. 36(12), 3093-3115 (2009).

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