Probing ultrafast phenomena with radially polarized light

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A new modality for probing ultrafast phenomena that relies on radially or azimuthally polarized probe pulses is presented. First, we describe the principle and then theoretically analyze the signals expected for different types of pump-induced nonlinearities. Last, we experimentally verify the methodology by probing a pump-induced Kerr gate with a time-delayed radially polarized probe pulse. In general, we find excellent agreement between the simulated and measured results.

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1. INTRODUCTION

Radially polarized laser beams are known to be advantageous for a number of different applications, e.g., laser cutting or drilling [1,2], trapping of micron-sized metallic particles [3,4], tight focusing of light [5], vacuum acceleration of electrons [6], or in light-scattering polarimetry [7,8]. In laser cutting, the radial polarization ensures that the electric field vector is always perpendicular to the cutting front, irrespective of the direction of cutting, and as a result the overall efficiency increases. For similar reasons, radially polarized light is predicted to be useful in the trapping of metallic particles as the net force due to reflection is uniform around the circumference. In microscopy and optical data storage, radially polarized light might become important because it can be focused to a smaller spot size than, for example, a Gaussian beam of similar size. Finally, intense radially polarized laser pulses may find applications in accelerating electrons to relativistic energies due to their strong longitudinal electric field component in the focal region.

There are several known techniques to realize a radially polarized laser beam and they may be divided in the following two subgroups: those relying on special optical elements inside the laser cavity, forcing the laser resonator to oscillate with a mode that exhibits radial polarization, and those using extra-cavity elements to convert a linearly polarized beam to a radially polarized beam. In 1972 two different intra-cavity techniques were already demonstrated. Mushiake and coworkers used a conical dielectric element [9] and Pohl inserted a calcite crystal in a ruby laser resonator [10] to favor the radially polarized mode. Today the most widely used intra-cavity elements are grating mirrors [11], Brewster axicons [2], dual conical prisms [12], and birefringent elements [13]. Most of them are applicable in solid state as well as in fiber or gas laser cavities. Initially all methods were demonstrated in continuous wave mode, but more recently have been shown to be applicable even in Q-switched [2] or mode-locked lasers [14].

The first extra-cavity method reported was based on an interferometer superimposing two linearly polarized beams in a specific way so that the resulting beam exhibited the desired polarization [15]. Techniques relying on a phase coherent superposition of two beams, however, are inherently sensitive to mechanical or thermal fluctuations. More stable alternatives are single-beam mode converters. For example, few-mode optical fibers have been shown to convert a Laguerre–Gaussian beam to a radially polarized beam [16]. Also, special liquid crystal devices are capable of generating radially or azimuthally polarized light [17].

Up to now, radially polarized beams have been used in single-beam applications, as described above. Here, we demonstrate that radially polarized light pulses can be advantageous in ultrafast pump-probe experiments, as probing with a radially polarized probe pulse allows for a simultaneous detection of ultrafast phenomena at all possible angles of linear polarization. First, we theoretically analyze the measurement scheme for different types of nonlinearities, i.e., pump-induced phase shift, polarization rotation, and dichroism in circular anisotropic media. To demonstrate the principle we experimentally investigate a pump-induced Kerr-phase.

2. MEASUREMENT CONCEPT

The concept of probing ultrafast events with radially polarized laser pulses is schematically depicted in Fig. 1(a). We assume that the laser system emits linearly polarized pulses with a Gaussian-shaped beam profile. They are split into pairs of pump and probe pulses with an adjustable time delay between...
the two. The probe pulses are directed through a liquid crystal cell (ARCoptix, Switzerland), converting the incoming linear polarization either to radial or azimuthal polarization. After the liquid crystal cell, the probe beam profile is doughnut-shaped due to the polarization singularity at the center of probe beam. The probe pulses are then focused to the sample and the doughnut-shaped radially or azimuthally polarized probe is overlapped with the Gaussian-shaped linearly polarized pump pulse. We assume that the pump beam has a similar or, ideally, even a larger diameter than the probe. Finally, the probe beam is imaged through a polarizer to a CCD camera.

Within the framework of Jones vectors and in spherical coordinates the spatial electric field distribution $E_0(r, \phi)$ of the radially or azimuthally polarized probe beam can be conveniently described through

$$E_0(r, \phi) = f(r, \phi)V_0(\phi),$$

with $f(r, \phi)$ determining the spatial beam profile. The Jones vector is

$$V_0(\phi) = \begin{bmatrix} \cos(p\phi + \phi_0) \\ \sin(p\phi + \phi_0) \end{bmatrix},$$

where $p$ is the polarization order number and $\phi_0 = 0, \pi/2$ distinguishes between radial and azimuthal polarization, respectively. When the probe light is radially polarized, the azimuthal angle coincides with the local polarization angle of the linearly polarized light. For azimuthally polarized light the local linear polarization of the probe is tangential to the azimuthal position [see Fig. 1(b)]. The sample is described by a Jones matrix $M(I_{\text{pump}}(r, \phi))$. Its properties depend on the sample itself but also on the time delay between the pump and probe and the pump intensity $I_{\text{pump}}(r, \phi)$. Therefore, $M$ is generally a function of the coordinates $(r, \phi)$. The polarizer is aligned at an angle $\alpha$ with respect to the horizontal (x) axis and described by

$$P(\alpha) = \begin{bmatrix} \cos^2 \alpha & \sin \alpha \cos \alpha \\ \sin \alpha \cos \alpha & \sin^2 \alpha \end{bmatrix}.$$  

The signal measured by the CCD camera is a function of the radius $r$ and the azimuthal angle $\phi$, as follows:

$$S(r, \phi) \propto |f(r, \phi)|P(\alpha)M(r, \phi)V_0(\phi)|^2.$$  

It depends on the radius because the pump and probe beam both vary with radius. The probe beam profile can be easily eliminated by normalizing the measured CCD images with respect to an image without the pump, i.e.,

$$R(r, \phi) = \frac{S(r, \phi)}{S(r, \phi)_{\text{no pump}}}.$$  

If the pump beam is larger than the probe beam, then the pump intensity can be assumed to be constant across the probe beam and $M(r, \phi)$ becomes independent of the coordinates $(r, \phi)$. Therefore, the CCD images $S(r, \phi)$ and $R(r, \phi)$ may be integrated along the radial coordinate to improve the signal-to-noise ratio.

In the following subsections, we theoretically analyze the measurement scheme for three different nonlinearities, i.e., a pump-induced phase shift, a pump-induced polarization rotation, and a pump-induced dichroism in a circular anisotropic medium. We show that the simultaneous measurement at all angles of polarization has numerous advantages; specifically, it allows for an easy and straightforward identification of the underlying nonlinear process. The coordinate system is oriented such that both pulses propagate parallel to the $x$ axis. The pump pulse is polarized along the horizontal $x$ axis and the electric field vector of the probe pulse has components along the $x$ axis, $E_x$, and along the $y$ axis, $E_y$.

### A. Pump-Induced Phase Shift

Consider a crystalline plate having parallel faces and a thickness of $L$ measured along the $x$ axis. If such a plate is illuminated with a plane wave under normal incidence it is known that only two orthogonal eigenstates of polarization may propagate through the plate. They define the $x'$ and $y'$ axes of the crystal’s coordinate system and waves with corresponding polarization experience different refractive indices. Typically, the slow axis (larger refractive index) is associated with the $x'$ axis. The difference in refractive indices $\Delta n = n_{x'} - n_x$ is the birefringence of the plate. The associated phase difference is given through

$$\Delta \phi = \phi_x - \phi_y = \frac{\alpha_0}{c} \Delta n L,$$

with the speed of light $c$ and the carrier frequency of the probe $\omega_0$. If the crystal’s coordinate system is rotated by an angle $\theta$ around the $x$ axis with respect to the laboratory coordinate system, its Jones matrix is

$$M = e^{i\psi} \begin{bmatrix} \cos \frac{\Delta \phi}{2} + i \cos 2\theta \sin \frac{\Delta \phi}{2} & i \sin 2\theta \sin \frac{\Delta \phi}{2} \\ i \sin 2\theta \sin \frac{\Delta \phi}{2} & \cos \frac{\Delta \phi}{2} - i \cos 2\theta \sin \frac{\Delta \phi}{2} \end{bmatrix},$$

with $\psi = (\phi_{x'} + \phi_y)/2$. For simplicity, we henceforth assume an isotropic medium. Since the pump pulse is polarized along the $x$ axis of the laboratory coordinate system, we have $\theta = 0$. The intense pump pulse gives rise to the Kerr effect, which induces a birefringence to the otherwise isotropic medium as follows:

$$\Delta n(r, \phi) = \left(\chi^{(3)}_{xx'z} + \chi^{(3)}_{zyz}\right)|E_{\text{pump}}(r, \phi)|^2.$$  

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**Fig. 1.** (a) Measurement concept. LC: liquid crystal, $V_0$: Jones vector of incident field, $M$: Jones matrix of sample, $P$: Jones matrix of polarizer, and $\tau$: time delay. (b) Experimental setup and the two possible states of polarization after the liquid crystal cell.
As a consequence, the pump pulse induces a phase shift

$$\Delta \phi(r, \phi) = \frac{\alpha_0}{c} (\chi^{(3)}_{xx} + \chi^{(3)}_{yy})|E_{\text{pump}}(r, \phi)|^2 L$$

$$= \frac{\alpha_0}{c} n_2 I_{\text{pump}}(r, \phi)L, \quad (9)$$

and Eq. (7) simplifies to

$$\mathbf{M}(r, \phi) = e^{i\psi(r, \phi)} \begin{pmatrix} e^{-i(\Delta \phi(r, \phi)/2)} & 0 \\ 0 & e^{i(\Delta \phi(r, \phi)/2)} \end{pmatrix}. \quad (10)$$

For this geometry, it is straightforward to calculate the variation of the CCD signal as a function of $r$ and $\phi$ and the pump-induced phase shift $\Delta \phi(r, \phi)$, as follows:

$$S(r, \phi) = \frac{|f(r, \phi)|^2}{2} \left[ 1 + \cos 2\alpha \cos[2(p\phi + \phi_0)] + \sin 2\alpha \sin[2(p\phi + \phi_0)] \cos \Delta \phi(r, \phi) \right]. \quad (11)$$

For radial polarization, i.e., $p = 1$ and $\phi_0 = 0$, and a polarizer angle of $\alpha = -45$ deg the signal simplifies to

$$S(r, \phi) = \frac{|f(r, \phi)|^2}{2} \left[ 1 - \sin 2\phi \cos \Delta \phi(r, \phi) \right]. \quad (12)$$

Figure 2 shows the azimuthal dependence of Eq. (12) ($r = \text{const.}$) for different pump-induced phase shifts. We assume a uniform spatial pump intensity across the entire probe beam. Without the pump the signal oscillates between zero and one, with a zero intensity line along the 45 deg diagonal and maximal intensity along the 135 deg diagonal. As the pump intensity, and thus the pump-induced phase shift, increases the amplitude of the sinusoidal oscillation around the average value of 0.5 decreases. When the phase shift approaches $\pi/2$ the amplitude vanishes and the signal becomes constant and independent on the azimuthal angle.

**B. Pump-Induced Polarization Rotation**

Next, we consider a plate that has rotary power or circular anisotropy and the two orthogonal eigenstates of polarization are the right- and left-handed circular states of polarization. The associated refractive indices are $n_R$ and $n_L$ and the difference in the refractive indices $\Delta n = n_R - n_L$ causes a phase difference $\Delta \phi = \phi_R - \phi_L$ in the laboratory coordinate system. The corresponding Jones matrix is

$$\mathbf{M} = e^{i\psi} \begin{pmatrix} \cos \frac{\Delta \phi}{2} & -\sin \frac{\Delta \phi}{2} \\ \sin \frac{\Delta \phi}{2} & \cos \frac{\Delta \phi}{2} \end{pmatrix}. \quad (13)$$

with $\psi \equiv (\phi_R + \phi_L)/2$. Equation (13) shows that $\mathbf{M}$ has the form of a rotation matrix, rotating the incident linear polarization by $\Delta \phi/2$. Again we assume an isotropic medium and the rotary power or the circular anisotropy is being induced by the pump beam, a situation that is found, for example, in laser-induced magnetization [18]. Generally, either $\phi_R$, $\phi_L$, or both may be modified in the presence of the pump pulse. The signal as a function of the pump-induced phase shift $\Delta \phi(r, \phi)$ is

$$S(r, \phi) = |f(r, \phi)|^2 \cos^2 \left( \frac{\Delta \phi(r, \phi)}{2} + p\phi + \phi_0 - \alpha \right). \quad (14)$$

For radial polarization, i.e., $p = 1$ and $\phi_0 = 0$, and a polarizer angle of $\alpha = -45$ deg the signal simplifies to

$$S(r, \phi) = |f(r, \phi)|^2 \cos^2 \left( \frac{\Delta \phi(r, \phi)}{2} + \phi + \frac{\pi}{4} \right). \quad (15)$$

Figure 3 shows the azimuthal dependence of Eq. (15) ($r = \text{const.}$) for different pump-induced phase shifts. We assume a uniform spatial pump intensity. Without the pump the signal vanishes along the 45 deg diagonal and is maximal along the 135 deg diagonal. With increasing pump intensity, the entire CCD image is rotated by an angle $\Delta \phi/2$. We would like to emphasize that the signal $S(r, \phi)$ observed for a pump-induced rotation is very different from that of a pump-induced phase shift and thus helps to distinguish between the two effects, as claimed in the introduction. This might be difficult if only one state of polarization is analyzed as is often the case in conventional pump-probe experiments.

**C. Pump-Induced Dichroism in Circular Anisotropic Media**

Finally, we consider a plate that shows dichroic circular anisotropy. The two orthogonal eigenstates of polarization are, again, the right- and left-handed circular states of polarization. In dichroic circular anisotropy the right- and left-handed waves experience not only a different phase shift but also a different absorption, $A_R$ and $A_L$. The corresponding Jones matrix is

$$\mathbf{M} = \frac{1}{2} \begin{pmatrix} (T_R e^{i\phi_R} + T_L e^{i\phi_L}) & -i(T_L e^{i\phi_L} - T_R e^{i\phi_R}) \\ i(T_L e^{i\phi_L} - T_R e^{i\phi_R}) & (T_L e^{i\phi_L} + T_R e^{i\phi_R}) \end{pmatrix}. \quad (16)$$

![Fig. 2.](image2.png) Theoretical signal [Eq. (12)] for a phase shifter as a function of the azimuthal angle $\phi$. The pump-induced phase shifts are $\Delta \phi = 0, 0.5, 1.0, 1.5$.

![Fig. 3.](image3.png) Theoretical signal [Eq. (15)] for a rotator as a function of the azimuthal angle $\phi$. The pump-induced phase shifts are $\Delta \phi = 0, 0.5, 1.0, 1.5$. 
and depends on the different transmissions, $T_R = 1 - A_R$ and
$T_L = 1 - A_L$, and/or phase shifts, $\phi_R$ and $\phi_L$. For
$T_R = T_L \equiv 1$, which is no absorption but different phases
$\phi_R$ and $\phi_L$, we find

$$M = e^{i\psi} \begin{bmatrix} \cos \frac{\Delta \phi}{2} & -i \sin \frac{\Delta \phi}{2} \\ i \sin \frac{\Delta \phi}{2} & \cos \frac{\Delta \phi}{2} \end{bmatrix}. \quad (17)$$

with $\psi = (\phi_R + \phi_L)/2$ and $\Delta \phi = \phi_R - \phi_L$. Not surprisingly, Eq. (17) is equivalent to Eq. (13) and thus the signal is given by
Eq. (14). If a dichroism, i.e., a difference in absorption, exists
but no difference in phases the Jones matrix becomes

$$M = \begin{bmatrix} T & i \Delta T \\ -i \Delta T & T \end{bmatrix}, \quad (18)$$

with $T = (T_R + T_L)/2$ and $\Delta T = (T_R - T_L)/2$. We
assume that an intense pump pulse induces such dichroism in
an otherwise isotropic medium. For such scenarios, the signal
versus radius and azimuthal angle is calculated as

$$S(r, \phi) = |f(r, \phi)|^2[T^2(r, \phi)\cos^2(\rho \phi + \phi_0 - \alpha) + \Delta T^2(r, \phi)\sin^2(\rho \phi + \phi_0 - \alpha)]. \quad (19)$$

Figure 4 shows the azimuthal dependence of Eq. (19)
($r = \text{const.}$) for increasing $\Delta T$. We assume a uniform spatial
pump intensity and consider radially polarized probe pulses,
i.e., $\rho = 1$ and $\phi_0 = 0$, and the polarizer at $\alpha = -45$ deg.
Without the pump the signal vanishes along the 45 deg diagonal
and is maximal along the 135 deg diagonal. The oscillation
amplitude and the average value decreases with increasing
pump intensity. Again, the signal shows a very distinct dependence
on the azimuthal angle that makes it easy to distinguish it from
the two cases discussed previously.

### 3. EXPERIMENT

For the experiments described we use horizontally polarized
laser pulses with a center wavelength of 800 nm, a bandwidth
of 10 nm, a pulse duration of approximately 100 fs, and a pulse
energy of up to 100 $\mu$J at a repetition rate of 1 kHz. The setup is
shown in Fig. 1(b). The pulses pass through a 90%/10% beam
splitter separating the pump from the probe. While the pump
pulses pass a mechanical delay line before being focused to the
sample, the probe pulses are directed through a liquid crystal

cell converting the polarization from horizontal to radial.
Horizontally polarized pump pulses and radially polarized
probe pulses are focused by a lens ($f_1 = 30$ cm) to the sample
in a noncollinear geometry. The size of the pump is adjusted
such that its diameter at the sample position is $(182 \pm 5)\mu$m
and is therefore larger than the probe diameter of $(73 \pm 5)\mu$m.
The sample was a 2 mm thick BK7 glass slide. Finally, a second
lens ($f_2 = 10$ cm) images the probe beam from the sample plane,
through a polarizer, to the CCD camera (8 bit CMOS detector with
1280 x 1024 pixels, each 5.2 $\mu$m in size). The images recorded are then integrated along the radial coordinate in a range
where the pump beam may safely be considered to have constant intensity. The resulting plots show the integrated
intensity as a function of the azimuthal angle.

The liquid crystal cell includes a polarization rotator, a
retarder cell, and a so-called $\Theta$-cell [17]. The $\Theta$ cell contains
twisted nematic liquid crystals that locally rotate the direction
of linear polarization. This liquid crystal device is achromatic
because it relies on rotation rather than phase retardance like a
half-wave plate.

The state of polarization after the liquid crystal cell is char-
acterized by measuring the beam profile after the polarizer
is oriented at different angles. Figure 5 shows four CCD images for
polarizer angles of 0 deg, 45 deg, 90 deg, and 135 deg, respec-
tively. The horizontal structures around the center of all
four images are diffraction patterns created by the ‘defect line’
of the retarder cell.

A radial polarization manifests itself in a figure eight shaped
intensity profile that rotates together with the polarizer as
seen in the sequence of images shown in Fig. 5. The fact that
the intensity drops to zero along the line perpendicular to the
polarizer axis corroborates the achromatic nature of the liquid
crystal cell. We also confirmed that neither the spectrum nor
the temporal intensity of the probe is affected by the liquid
crystal cell. In other words, we demonstrated that it is indeed
possible to generate 100 fs duration probe pulses that exhibit
either a radial or an azimuthal state of polarization.

![Fig. 4](image-url)  
**Fig. 4.** Theoretical signal [Eq. (19)] for a pump-induced dichroic
circular anisotropy as a function of the azimuthal angle $\phi$. The
differences in transmission are $\Delta T = 0, 0.1, 0.2, 0.3$.

![Fig. 5](image-url)  
**Fig. 5.** CCD images of the radially polarized probe beam after a
polarizer for different polarizer angles, i.e., (a) 0 deg, (b) 45 deg,
(c) 90 deg and (d) 135 deg, respectively.
4. RESULTS

We start with analyzing the pump-induced Kerr phase shift at a time delay of zero between the pump and probe. As stated in Eq. (11), with no pump beam present the signal varies as $1 - \sin 2\phi$ and exhibits zero intensity for $\phi = (2n + 1)\pi/4$; that is, along the diagonal through the first and third quadrant, and the maximal intensity along the diagonal through the second and the fourth quadrant, respectively. Figure 6(a) shows a CCD image with the pump beam blocked.

For an increasing pump intensity, the contrast decreases until it vanishes completely for $\Delta\phi = \pi/2$. Qualitatively, the reduction in contrast for a pump intensity of 160 GW/cm$^2$ can already be seen in Fig. 6(b) along the 45 deg diagonal. The azimuthally dependent signal is obtained by integrating the CCD image along the radial direction from the inner to the outer red circle shown in Fig. 6(a), i.e.,

$$S\phi = \frac{1}{2} \int_{r_{\text{min}}}^{r_{\text{max}}} \sin^2(\phi, \theta)(1 - \sin 2\phi \cos \Delta\phi)$$

$$= \frac{\beta(\phi)}{2} (1 - \sin 2\phi \cos \Delta\phi). \tag{20}$$

Figure 7(a) shows the calculated [Eq. (20), solid curves] as well as the measured signal (open circles) as a function of the azimuthal angle $\phi$ without a pump (blue) and with a pump (red). For the calculation, we assume that the probe beam profile is uniform within the outer red circle shown in Fig. 6(a), and a value of $I_{\text{pump}}$. Comparing the red to the blue curve indicates a reduction in contrast when the pump pulse is overlapped with the probe. In order to eliminate azimuthal inhomogeneities in the probe pulse profile it is convenient to normalize the measured signal, as stated earlier, and here we find

$$R\phi = \frac{1 - \sin 2\phi}{1 - \sin 2\phi \cos \Delta\phi}. \tag{21}$$

The experimental result (circles) together with Eq. (21) (solid curve) are shown in Fig. 7(b). For the calculations we use $n_2 = 3.5 \cdot 10^{-16}$ cm$^2$/W for the 2 mm thick BK7 glass slide, the measured pump beam diameter of 182 $\mu$m, and the measured pump intensity of 300 GW/cm$^2$. While for all angles above 135 degrees the agreement between the simulated and measured results is excellent, there are some deviations for smaller angles. These are most likely due to an inhomogeneous pump pulse profile or an imperfect spatial overlap between the pump and probe pulses.

Figure 6. CCD images of the probe beam profile after the polarizer (a) without and (b) with a pump pulse at zero time delay. The two red circles in (a) mark the inner and outer limits of the radial integration.

Next, we investigate the intensity dependence of the signal. A convenient measure is the maximum contrast, i.e., $\Delta S = S\phi - S\phi = 45 - S\phi = 45$, and with Eq. (12) we find

$$\Delta S \propto \cos \Delta\phi = \frac{o_0n_2I_{\text{pump}}^L}{c}, \tag{22}$$

assuming $\beta$ is uniform in $\phi$. Figure 8 shows the measured (blue filled circles) and the simulated (red solid curve) maximum contrasts, and we find reasonable agreement up to the highest pump intensities used.

Finally, we measured the signal as a function of the pump probe time delay $r$. Figure 9 shows a color-coded plot of the integrated intensity $S\phi(r, \phi)$ as a function of pump-probe time.
the pump probe time delay $\tau$ and azimuthal angle $\phi$. The azimuthal intensity varies between the two extreme cases shown in Fig. 7(a) within a range of approximately 200 fs around time zero and this time interval is consistent with the pulse duration measured. In fact, the signal variations versus time delay must follow a third-order intensity correlation as the Kerr effect is instantaneous on the time scales relevant here.

5. CONCLUSION

In conclusion, we have demonstrated a novel methodology for probing ultrafast phenomena using radially or azimuthally polarized probe pulses. First, we have shown that it is indeed possible to generate radially or azimuthally polarized probe pulses, at least down to pulse durations of approximately 100 fs. The new probing scheme allows for a simultaneous detection of all angles of linear polarization and thus offers a number of distinct advantages over conventional probing schemes. First, the trend of the measured signal variations indicates the type of the nonlinearity induced by the pump. A decreasing contrast is indicative for a pump-induced phase shift, a pure horizontal shift for a pump-induced polarization rotation, and a reduced contrast accompanied by a lowered average value for a pump-induced dichroic circular anisotropy. Second, the simultaneous recording of all states of polarization significantly reduces the overall measurement time and increases the accuracy of the extracted material properties.

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**REFERENCES**