Measurement of the degree of temporal coherence of unpolarized light beams

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We measure the electromagnetic degree of temporal coherence and the associated coherence time for quasi-monochromatic unpolarized light beams emitted by an LED, a filtered halogen lamp, and a multimode He–Ne laser. The method is based on observing at the output of a Michelson interferometer the visibilities (contrasts) of the intensity and polarization-state modulations expressed in terms of the Stokes parameters. The results are in good agreement with those deduced directly from the source spectra. The measurements are repeated after passing the beams through a linear polarizer so as to elucidate the role of polarization in electromagnetic coherence. While the polarizer varies the equal-time degree of coherence consistently with the theoretical predictions and alters the inner structure of the coherence matrix, the coherence time remains almost unchanged when the light varies from unpolarized to polarized. The results are important in the areas of applications dealing with physical optics and electromagnetic interference. © 2017 Chinese Laser Press

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1. INTRODUCTION

In traditional Michelson's interferometer [1] with scalar light beams, the intensity fringes at the output are a manifestation of temporal coherence associated with the field [2,3]. More precisely, the visibility of the intensity modulation equals the degree of temporal coherence enabling, in particular, to assess the coherence time of the light. However, in the case of random electromagnetic beams, which may have an arbitrary degree of polarization and for which a scalar-wave treatment is generally not sufficient, not only the intensity, but also, or only, the polarization characteristics (state and degree) can be modulated in interference [4]. This has been shown for spatial coherence in Young's interferometer [5,6], where the coherence (twopoint) Stokes parameters [7,8] at the pinholes specify the conventional polarization (one-point) Stokes-parameter variations on the observation screen [9].

Not long ago, a relationship between the coherence and polarization Stokes parameters in Michelson's interferometer was established for the evaluation of the temporal coherence of quasi-monochromatic light beams [10]. This electromagnetic interference law allows us to express the degree of temporal coherence of the incident field as a sum of the visibilities of the Stokes-parameter modulations at the output plane [9]. In particular, it enables us to assess the coherence time of a light beam possessing any degree and state of polarization and thereby extends the studies of temporal coherence beyond scalar fields. The method is based on considering the electric-field correlations and

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differs from a recent study where the temporal coherence of specific unpolarized light beams was measured in terms of intensity correlations using two-photon absorption and polarizationsensitive Michelson's interferometer [11].

In this work, we employ the electromagnetic interference law in Michelson's interferometer and measure the degree of temporal coherence and the coherence time for quasi-monochromatic, unpolarized and polarized, light beams produced by an LED, a halogen lamp, and a He–Ne laser source. The results are found to be in excellent agreement with those obtained directly from the spectra and illustrate the role of polarization in electromagnetic temporal coherence. In particular, the polarization properties affect the degree of temporal coherence at small time differences, but the coherence time does not change significantly when the light beam varies from unpolarized to polarized.

2. MICHELSON'S INTERFEROMETER AND TEMPORAL STOKES-PARAMETER MODULATIONS

Consider a statistically stationary, quasi-monochromatic, uniformly partially polarized random light beam taken to propagate along the *z* axis. A realization of the field, at time *t*, is represented by the (position-independent) column vector $\mathbf{E}(t) = [E_x(t), E_y(t)]^T$, where T denotes the transpose. The temporal coherence properties of such a light field, at a time difference τ , are described in terms of the 2 × 2 mutual coherence matrix defined as $\Gamma(\tau) = \langle \mathbf{E}^*(t)\mathbf{E}^{\mathrm{T}}(t+\tau)\rangle$ [2,12], where the angle brackets and asterisk denote time averaging (or ensemble averaging due to ergodicity) and complex conjugation, respectively.

The electromagnetic degree of coherence (in squared form) is defined as [6,13,14]

$$\gamma^{2}(\tau) = \frac{\operatorname{tr}[\Gamma(\tau)\Gamma(-\tau)]}{\operatorname{tr}^{2}[\Gamma(0)]},$$
(1)

where tr denotes the trace and tr[$\Gamma(0)$] is the average field intensity. The quantity $\gamma(\tau)$ is real and bounded between 0 and 1, the two limits corresponding to temporal incoherence (no correlation between the field components at τ) and temporal coherence (all components are fully correlated at τ), respectively. We remark that alternative definitions for the degree of coherence of electromagnetic beam fields have been put forward (see, for instance, [9,15]). Besides the mutual coherence matrix, the coherence properties of an electromagnetic field can be described in terms of the coherence Stokes parameters introduced as [6–8,16]

$$S_0(\tau) = \Gamma_{xx}(\tau) + \Gamma_{yy}(\tau), \qquad (2)$$

$$S_1(\tau) = \Gamma_{xx}(\tau) - \Gamma_{yy}(\tau), \qquad (3)$$

$$S_2(\tau) = \Gamma_{xy}(\tau) + \Gamma_{yx}(\tau), \qquad (4)$$

$$S_3(\tau) = i[\Gamma_{yx}(\tau) - \Gamma_{xy}(\tau)],$$
(5)

where $\Gamma_{ij}(\tau) = \langle E_i^*(t)E_j(t+\tau) \rangle$ and $(i, j) \in (x, y)$ are the elements of matrix $\Gamma(\tau)$. The coherence Stokes parameters appear as the expansion coefficients when $\Gamma(\tau)$ is expressed in terms of the Pauli matrices [16]. Explicitly,

$$\Gamma(\tau) = \frac{1}{2} \sum_{n=0}^{3} S_n(\tau) \boldsymbol{\sigma}_n,$$
(6)

where the Pauli matrices are [2]

$$\boldsymbol{\sigma}_{0} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \qquad \boldsymbol{\sigma}_{1} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix},$$
$$\boldsymbol{\sigma}_{2} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \qquad \boldsymbol{\sigma}_{3} = \begin{bmatrix} 0 & i \\ -i & 0 \end{bmatrix}.$$
(7)

When $\tau = 0$, the (complex) coherence Stokes parameters in Eqs. (2)–(5) reduce to the (real) polarization Stokes parameters given as [2]

$$S_0 = J_{xx} + J_{yy},\tag{8}$$

$$S_1 = J_{xx} - J_{yy}, \tag{9}$$

$$S_2 = J_{xy} + J_{yx}$$
, (10)

$$S_3 = i(J_{yx} - J_{xy}),$$
 (11)

where $J_{ij} = \Gamma_{ij}(0)$, $(i, j) \in (x, y)$, are the elements of the polarization matrix **J** [2]. In addition, Eq. (6) reduces to the wellknown expansion of the polarization matrix [2]. Employing the coherence and polarization Stokes parameters, the degree of coherence in Eq. (1) assumes an alternative form:

$$\gamma^{2}(\tau) = \frac{1}{2} \sum_{n=0}^{3} |\gamma_{n}(\tau)|^{2},$$
 (12)

where the quantities $\gamma_n(\tau) = S_n(\tau)/S_0$, $n \in (0, ..., 3)$, are simply the intensity-normalized coherence Stokes parameters [6].

In this work, we measure the temporal coherence of various light beams using Michelson's interferometer, as illustrated schematically in Fig. 1. The beam incident onto the device is divided into two arms by a nonpolarizing 50:50 beam splitter (BS). The fields then reflect back from the mirrors and interfere at the output. The time difference τ between the waves from the two arms can be adjusted by translating one of the mirrors. At the output, the polarization Stokes parameters are given by the following electromagnetic interference law [10]:

$$S_n(\tau) = \frac{1}{2} S_n^{(i)} + \frac{1}{2} S_0^{(i)} |\gamma_n^{(i)}(\tau)| \cos[\alpha_n(\tau) + \Delta \phi - \omega_0 \tau], \quad (13)$$

with $n \in (0, ..., 3)$. The superscript (i) is here and henceforth used to denote the incident beam if needed for clarity, while $\Delta \phi$ is a (deterministic) relative phase shift between the fields from the two arms induced by reflections and transmissions at the interfaces. In particular, $\alpha_n(\tau) = \arg[\gamma_n^{(i)}(\tau)] + \omega_0 \tau$, where arg is the phase of complex number and ω_0 is the center (angular) frequency of the light. Beams we consider in this work are quasi-monochromatic; hence $|\gamma_n^{(i)}(\tau)|$ and $\alpha_n(\tau)$ are slowly varying with τ . It follows that the Stokes parameters are, in a sufficiently large τ range, sinusoidally modulated with the period $\tau_p = 2\pi/\omega_0$. This period corresponds to a halfwavelength difference in the arm lengths. Because the incident field is uniform, the visibility of the output Stokes-parameter modulations (when τ is varied) becomes

$$V_{n}(\tau) = \frac{\max[S_{n}(\tau)] - \min[S_{n}(\tau)]}{\max[S_{0}(\tau)] + \min[S_{0}(\tau)]} = |\gamma_{n}^{(i)}(\tau)|, \quad (14)$$

for $n \in (0, ..., 3)$ and where max/min refer to the maximum/ minimum value in the neighborhood of τ . It follows from Eq. (12) that the electromagnetic degree of coherence of the incident beam obeys (see also Ref. [10])

$$\gamma^{(i)}(\tau) = \left[\frac{1}{2}\sum_{n=0}^{3}V_{n}^{2}(\tau)\right]^{1/2}.$$
 (15)

Hence, in full analogy to what earlier has been found for spatial coherence in Young's interferometer [5,6], the temporal electromagnetic degree of coherence is directly given by the



Fig. 1. Illustration of Michelson's interferometer. An incident beam is split into arms 1 and 2 by a BS. The fields reflect back from the mirrors (M) and propagate to the output via the BS again. The length of arm 2 can be adjusted by translating the mirror, yielding to a time delay τ between the fields from the two arms.

visibilities of the polarization Stokes-parameter modulations at the output of Michelson's interferometer [9,10].

It is of interest to consider separately the electromagnetic interference of fully polarized beams. For such light we may write $\mathbf{E}(t) = \hat{\mathbf{e}}E(t)$, where $\hat{\mathbf{e}}$ is a deterministic unit vector defining the polarization state and E(t) is a random scalar function. For this field the mutual coherence matrix is $\Gamma(\tau) = \mathbf{J}\gamma_s(\tau)$, where $\mathbf{J} = \hat{\mathbf{e}}^* \hat{\mathbf{e}}^T \Gamma(0)$ is the polarization matrix and $\gamma_s(\tau) = \Gamma(\tau)/\Gamma(0)$, with $\Gamma(\tau) = \langle E^*(t)E(t+\tau) \rangle$, is the degree of coherence of the scalar field E(t). Therefore, $S_n(\tau) = S_n\gamma_s(\tau)$ for all $n \in (0, ..., 3)$, and consequently

$$\sum_{n=1}^{3} V_n^2(\tau) = V_0^2(\tau) = |\gamma_s(\tau)|^2,$$
 (16)

where we used the fact that $S_1^2 + S_2^2 + S_3^2 = S_0^2$ holds for polarized light. Thus, for any fully polarized light beam, the sum of the squared visibilities related to the polarization modulation represented by S_n , with $n \in (1, 2, 3)$, equals the squared visibility of the intensity variations. Moreover, $\gamma(\tau) = |\gamma_i(\tau)|$, as shown in Eq. (12). This, in turn, demonstrates the fact [13] that, for a fully polarized field, whose coherence properties can be treated within the scalar framework, the electromagnetic degree of coherence reduces to the traditional degree of coherence of scalar fields.

The temporal degree of coherence in Eq. (15) enables us to assess the coherence time τ_c over which the electric field components of the incident beam are sufficiently correlated so as to produce significant interference that appears either as intensity or polarization-state modulation or both. However, being a characteristic measure, no unique definition exists for the coherence time even in the context of scalar fields. Therefore we may choose the one employed in Section 4.3.3 of Ref. [2], which analogously for electromagnetic fields reads as

$$\tau_c^2 = \frac{\int_{-\infty}^{\infty} \tau^2 \gamma^2(\tau) \mathrm{d}\tau}{\int_{-\infty}^{\infty} \gamma^2(\tau) \mathrm{d}\tau},$$
(17)

stating that the coherence time is the normalized root-meansquare (rms) width of the squared electromagnetic degree of coherence $\gamma(\tau)$.

We emphasize that, unlike with scalar fields, the degree of coherence in Eq. (1) does not necessarily become unity for $\tau = 0$. Instead, we straightforwardly find that [13]

$$\gamma^2(0) = \frac{1}{2}(P^2 + 1),$$
 (18)

where *P* is the degree of polarization of the beam [2]. Thus, $1/\sqrt{2} \le \gamma(0) \le 1$, the two limits corresponding to an unpolarized (*P* = 0) and a polarized (*P* = 1) beam, respectively. The fact that $\gamma(0)$ is not equal to one for all fields is physically understandable. For example, an unpolarized beam is composed of two uncorrelated orthogonally polarized modes and therefore cannot be viewed as fully coherent even for $\tau = 0$.

3. MEASURING THE TEMPORAL ELECTROMAGNETIC DEGREE OF COHERENCE

We measure the temporal coherence properties of the electromagnetic beam fields by employing a modified Michelson interferometer, as depicted in Fig. 2. Light from the source



Fig. 2. Illustration of the used measurement setup. Collimating optics render the light from the source beam-like. The beam is split into arms 1 and 2 with a nonpolarizing BS. The mirror (M) in arm 2 is translated by a piezo element, yielding a controllable time difference τ between the fields from the two arms, and their interference is observed with a CMOS camera. To transform the variations of the polarization Stokes parameters into intensity modulation, suitable quarter-wave plates $\mathbf{Q}(\theta)$, where θ is the angle the fast axis of the wave plate created with the *x* axis, are placed into the two arms.

is collimated to produce a beam-like field, which then impinges onto a 50:50 nonpolarizing BS. This divides the beam into two equal-intensity parts and guides them into arms 1 and 2. The length of arm 2, and consequently the time difference τ between the two beams, is controlled with a linear piezo positioning stage capable of movement with 0.2 nm resolution (corresponding to $\tau = 0.0013$ fs). Finally, beams from both arms propagate via mirrors (M) and the BS to a CMOS camera, which records the intensity. The interferometer is equipped in both arms with quarter-wave plates $\mathbf{Q}(\theta)$, where θ is the angle the fast axis of the wave plate made with the *x* axis. The function of the wave plates is to transform the modulation in the polarization Stokes parameters, S_n with $n \in (1, 2, 3)$, into measurable intensity variations represented by S_0 [10].

The complete characterization of the electromagnetic degree of temporal coherence requires in total four measurements, one for the visibility of each Stokes-parameter modulation. Specifically, intensity $S_0(\tau)$ is measured directly (without the wave plates), but for the other three parameters, as shown in Ref. [10], the following wave-plate combinations are required:

- 1. **Q**(0) in arm 2 and arm 1 empty transfer $S_1(\tau)$ into $S_0(\tau)$.
- 2. $\mathbf{Q}(\pi/4)$ in arm 2 and arm 1 empty transfer $S_2(\tau)$ into $S_0(\tau)$.
- 3. **Q**(0) and **Q**($\pi/4$) in arm 2 and **Q**(0) in arm 1 transfer $S_3(\tau)$ into $S_0(\tau)$.

Inserting the measured visibilities in Eq. (15), results in the electromagnetic degree of coherence of the incident field as a function of τ .

4. LED

The first light source we consider is an LED emitting at red with the spectrum shown in Fig. 3 (solid red line). The peak wavelength is 633.8 nm, and the FWHM of the spectrum is 20 nm. The source is known to be highly unpolarized. For this source, the mirror in arm 2 is translated in 40 nm steps, and at each step (corresponding to a certain τ value) the intensity at



Fig. 3. Measured spectra of the considered light sources: an LED with the center wavelength of 633.8 nm (solid red line), filtered light from a halogen lamp (dashed blue line) with the bandwidth of 10 nm and center wavelength of 634.5 nm, and a He–Ne laser of the wavelength 632.8 nm (yellow vertical line).

the interferometer output is measured. Four measurements are performed, one for each Stokes parameter, as described above.

As an example, $S_0(\tau)$ (output intensity) for this LED is illustrated in Fig. 4. As seen from the inset, the intensity oscillates rapidly with the period of $\tau_p = 2.1$ fs, which covers seven mirror translation steps. The visibility of these variations, $V_0(\tau)$ calculated from Eq. (14) by considering the minimum and maximum value within one period, is illustrated in Fig. 5(a) with the blue curve. The visibilities of the other output Stokes parameters are obtained in the same way, but with wave plates in the arms, as described in Section 3. These are shown in Fig. 5(a) with the red dashed $[V_1(\tau)]$, yellow dot dashed $[V_2(\tau)]$, and purple dotted $[V_3(\tau)]$ curves. According to the definitions of $\gamma_n(\tau)$ and $V_n(\tau)$ given in Section 2, $|S_n^{(i)}(\tau)| = S_0^{(i)} V_n(\tau)$, implying that the relative magnitudes of the visibilities represent the relative contributions of the various terms in the expansion of Eq. (6), providing information on the inner structure of the mutual coherence matrix $\Gamma(\tau)$.

Inserting the visibility distributions shown in Fig. 5(a) into Eq. (15) results in the degree of temporal coherence depicted in Fig. 5(b) with the blue curve. The maximum value $\gamma(0) = 0.68$ is close to $1/\sqrt{2} \approx 0.71$, corresponding to an unpolarized beam (P = 0) as stated by Eq. (18). In addition, the coherence time defined in Eq. (17) is 24 fs, amounting to a (longitudinal) coherence length of 7.2 µm. For comparison, the degree of



Fig. 4. Intensity, S_0 , of the LED source as a function of τ at the output of Michelson's interferometer. Inset shows a magnified section over a short τ range demonstrating the oscillatory behavior of $S_0(\tau)$.



Fig. 5. Illustration of the temporal coherence properties of an LED source. (a) Visibilities of the Stokes-parameter modulations for unpolarized LED light. (b) Temporal electromagnetic degree of coherence obtained from the visibilities (blue curve, maximum value $\gamma(0) = 0.68$, coherence time $\tau_c = 24$ fs) and by Fourier transforming the spectrum (red crosses). Panels (c) and (d) are as in (a) and (b), respectively, but for polarized LED light. In (d) the maximum value is $\gamma(0) = 0.9$ and $\tau_c = 22$ fs.

coherence was calculated by Fourier transforming the measured spectrum, and the results are shown with red crosses in Fig. 5(b). The agreement is good.

Next we place a polarizer in front of the interferometer that renders the field fully polarized (P = 1) with an arbitrary linear state of polarization. The above four measurements are repeated, and the ensuing visibilities of the Stokes-parameter modulations and the degree of coherence are shown in Figs. 5(c) and 5(d), respectively. The visibility distributions have changed significantly due to the altered polarization; hence the inner structure of $\Gamma(\tau)$ has likewise changed. To a good accuracy $V_1^2(\tau) + V_2^2(\tau) + V_3^2(\tau) = V_0^2(\tau)$, consistently with the notions made in Section 2 for a fully polarized light. Regarding the coherence time, the value $\tau_c = 22$ fs found demonstrates that the temporal coherence is not significantly affected by the polarizer. However, the maximum at $\tau =$ 0 is increased to 0.90, approaching the theoretical value of 1 of polarized light [cf., Eq. (18)]. The difference probably originates from a small misalignment of the interferometer arms, which at the output leads to a spatial displacement of the two beams that reduces the temporal coherence if the transverse coherence length is sufficiently small. This explains why the measured $\gamma(0)$ for all unpolarized and polarized light beams considered in this work is slightly less than the corresponding theoretical value.

5. HALOGEN LAMP

The second source is a halogen lamp, which emits unpolarized broadband light. In order to conform to quasi-monochromaticity, under which the theory in Section 2 is valid, the radiation is spectrally filtered with a laser line filter. The spectrum after



Fig. 6. Temporal coherence properties of filtered light from a halogen lamp. (a) Visibilities of the Stokes-parameter modulations for unpolarized light. (b) Temporal electromagnetic degree of coherence obtained from the visibilities (blue curve, maximum value $\gamma(0) = 0.66$, coherence time $\tau_c = 53$ fs) and by Fourier transforming the spectrum of the light (red crosses). Panels (c) and (d) are as in (a) and (b), respectively, but for polarized lamp light. In (d) the maximum value is $\gamma(0) = 0.94$ and $\tau_c = 57$ fs.

filtering is shown in Fig. 3 by the dashed blue curve (bandwidth 10 nm, center wavelength 634.5 nm).

The mirror in arm 2 of the interferometer is moved in 20 nm steps, and the visibilities of all the four Stokes-parameter variations as a function of delay τ are measured. The results are shown in Fig. 6(a) and the related electromagnetic degree of coherence in Fig. 6(b). The maximum degree of coherence is $\gamma(0) = 0.66$, in qualitative agreement with $\gamma(0) = 0.71$ pertaining to an unpolarized beam. However, due to the narrower spectral bandwidth, the coherence time is longer, $\tau_c = 53$ fs, corresponding to a coherence length of 16 µm.

As with the LED, we polarized the light (arbitrary linear state of polarization) and repeated the four measurements. The ensuing visibilities of the Stokes-parameter modulations and the degree of coherence are shown in Figs. 6(c) and 6(d). Equation (16) was again found to hold to a good accuracy. The altered visibility curves imply that the inner structure of $\Gamma(\tau)$ has changed. Due to the polarizer, the maximum value of the degree of coherence has increased to $\gamma(0) = 0.94$, while the coherence time, $\tau_c = 57$ fs, is practically the same as in the unpolarized case. These observations are as expected because the coherence and polarization characters of a random electromagnetic field cannot, in general, be treated separately. Thus the modification of polarization may significantly alter the vectorial coherence characteristic [$\gamma(0)$ alters] but leave the coherence time almost unchanged.

6. LASER

The third source is an unpolarized multimode He–Ne laser (LGK7621MM) having the wavelength of 632.8 nm (yellow vertical line in Fig. 3). Again, we measure the visibilities of



Fig. 7. Temporal coherence properties of a He–Ne laser source. (a) Visibilities of the Stokes-parameter modulations when the beam is unpolarized. (b) Temporal electromagnetic degree of coherence (maximum value $\gamma(0) = 0.66$, coherence time $\tau_c = 0.71$ ns). Panels (c) and (d) are as in (a) and (b), respectively, but for a polarized laser beam. In (d) the maximum value is $\gamma(0) = 0.88$ and $\tau_c = 0.63$ ns.

the Stokes-parameter modulations when the light beam is unpolarized and polarized (with an unspecified linear state of polarization). Because the spectrum is narrow compared with the LED and the halogen-lamp light, the coherence time is expected to be longer than in those cases. For this reason, we utilized an additional motorized linear translation stage in arm 2 of the interferometer in order to increase the range of the time delay τ . The mirror was translated in 5 mm increments with the motorized stage. At each step the mirror was then moved by 20 nm steps with the piezo stage over two modulation periods, which is sufficient for the deduction of the local visibility.

The visibilities and the degree of temporal coherence for the laser source are shown in Figs. 7(a) and 7(b) for the unpolarized light, while Figs. 7(c) and 7(d) show them for the polarized beam. The maximum values of the degrees of coherence for the unpolarized and polarized beams are $\gamma(0) = 0.66$ and $\gamma(0) = 0.88$, respectively, demonstrating the effect of the polarizer. The coherence times in the two cases are $\tau_c=0.71\,$ ns (unpolarized) and $\tau_c = 0.63$ ns (polarized) showing that, again, the coherence time evaluated from the electromagnetic degree of coherence is almost unaffected by the degree of polarization even though the peak value of $\gamma(\tau)$ changes. In the case of polarized light, Eq. (16) was found to hold. The relatively long coherence time of the laser source corresponds to a coherence length of 20 cm. In contrast with the two other sources, the laser spectrum was not available to us, and the degree of coherence deduced from the spectrum is therefore not shown.

7. CONCLUSIONS

In conclusion, we have measured the temporal electromagnetic degree of coherence and the associated coherence time from the Stokes-parameter modulations at the output of Michelson's interferometer. Three quasi-monochromatic sources were

considered: an LED, a (filtered) halogen lamp, and a multimode He-Ne laser. All sources were unpolarized, but for each we performed the measurements also on passing the beam through an arbitrarily oriented linear polarizer. Due to the polarizer, the equal-time degree of coherence increases approximately from $1/\sqrt{2}$ to close to 1, which, respectively, corresponds to the theoretical values for unpolarized and polarized beams. In contrast, the coherence time did not significantly change in the process. For the LED and halogen lamp sources in both unpolarized and polarized cases, the degrees of coherence were in good agreement with those calculated directly from the spectra. For all polarized sources, the sum of the squared visibilities related to the polarization-state modulation was found to be equal to the squared visibility of the intensity modulation consistently with theoretical predictions. The results elucidate the relationship between polarization and electromagnetic coherence of light fields.

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