A scheme for data encryption and transmission using temporal correlation-based spectral switches

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A B S T R A C T

We present a method for data encoding in terms of spectral shifts in the source spectra. The spectral switching of polychromatic light due to temporal correlation, around the intensity minima in a Michelson Interferometer (MI) has been utilized for this purpose. The potential application of the encoding method for free space communication is described in detail. The advantages of this method are compared with the proposed schemes of data communication using spectral switches. The experimental constraints of this method are also discussed.

Keywords:
Michelson interferometer
Spectral shift
Spectral switch

1. Introduction

In recent years, extensive theoretical and experimental study has been carried out to investigate spectral behavior of polychromatic partially coherent light in the neighbourhood of intensity minima in interference or diffraction [1–11]. Not long ago a new branch of optics called "singular optics" has developed gradually in which the properties of the zero intensity and undetermined phase points in the optical field called "singular points" are studied [2]. The complex structure of optical field in the vicinity of such points leads to wave dislocations and optical vortices [2,3]. The spectral properties of partially coherent light passing through an aperture [7,8] and aperture lens [9] were studied and spectral changes were observed in the region of phase singularity of the focused waves [11]. Similar studies were made with Young's interference experiment [12].

Experimental observations of the spectra around the phase singularity in a single pinhole diffraction pattern show that at a particular diffraction angle, the diffracted spectrum splits into two halves, while at other diffraction angles the spectrum either shifts towards lower wavelengths (blue shift) or shifts towards higher wavelengths (red shift). This drastic change in spectrum that takes place in the vicinity of singular points is named as "spectral switch". This switching in spectrum was obtained in the vicinity of the dark ring of the Airy pattern [7–9]. Moreover, the behavior of the spectrum in the Fraunhofer region around a small circular loop centered at a critical direction was also studied [10].

One of the proposed applications of spectral switches was encoding data for free space communication [12]. This was proposed to be possible either by changing the spectral width or by modulating spatial coherence of the source. In the recent past, spectral anomalies were investigated for a polychromatic beam reflected from the interface of two homogeneous dielectric media at the neighbourhood of Brewster's angle [13]. Later it was also shown that for a right angle aperture, spectral switches can be obtained by adjusting the hypotenuse's slope [14]. It was also proposed that by changing the diffraction angle of an annular aperture, the data encoding and hiding mechanism might be possible [15].

It was shown for the first time that spectral changes take place in the neighbourhood of dark fringes in the interference pattern produced due to temporal correlation in Michelson interferometer using a white light source [16]. In this study red shift, blue shift and two-peak spectrum were obtained for different values of path difference introduced by moving a mirror in one of the arms of the interferometer. However, the constraints in this experimental system are rather apparent.

We propose a user friendly system which offers ease for modifying the experimental parameters to observe spectral switches and also show its potential application for information encoding and free space communication. In this scheme, a bit of data is encoded in terms of red shift or blue shift of the source spectrum at the transmitter end. After transmitting up to appreciable distances through free space, the spectrum is received and decoded at the receiver end using competent detectors and computer algorithm. The simplicity and ease in information encoding and transmission using this kind of spectral switches might provide an edge over the other recently proposed encoding schemes of free space communications [15].

2. Spectral switches produced by a Michelson interferometer

The spectrum of a white light source shows anomalous behavior when observed in the vicinity of a dark fringe in the interference pattern obtained due to temporal correlation. In the Michelson interferometer, the mirror in one arm is kept fixed while the other is moved along the beam direction using a precision nano-positioner (Fig. 1). A fiber-coupled spectrometer is used to measure the spectrum in the observation plane. The tip of the fiber is put on the dark ring at the observation plane and is moved across it precisely to observe the spectral shift.

An alternative way is to keep the fiber tip fixed, and introducing a path difference between both the arms of the interferometer by changing the position of the moving mirror. This change in the path delay makes the interference fringes at the observation plane either collapse toward the center or emerge out from the center (Fig. 2). This converging or diverging nature of the fringes shifts the position of the observation point P (position of the fiber tip) at the dark fringe. In other words, due to the movement, the maxima condition is satisfied for a different wavelength of the polychromatic light, while the previous wavelength has a minima at that point. This gives a shift in the observed peak spectrum. Thus the change in source spectra could be recorded with the change in path delay.

When the moving mirror is at position M_1 (Fig. 1), distances between the beam-splitter and mirrors in both the arms are assumed to be same within experimental uncertainty. This keeps the path difference close to 0. At the observation point P, we get the source spectrum without any spectral shift (Fig. 3). Moving the mirror outwards, the spectrum starts shifting toward red end and for M_2 position, i.e. for a path difference of 0.78 μm, we get the maximum red shift. At position M_3 the path difference is 0.95 μm and the spectrum splits into two asymmetric peaks having equal intensity. The position M_4 is achieved by moving the mirror in the same direction and for a path delay of 1.12 μm we get the maximum blue shift. At position M_5, the path difference is 1.33 μm and the source spectrum retraces itself.

If $S_0(\lambda)$ is the source spectrum and $\Delta\ell$ is the path difference between the two interfering beam paths, the spectra at any point in the observation plane $S(\lambda)$ can be calculated as [16]

$$S(\lambda) = \frac{1}{2} S_0(\lambda)\left[1 + \cos\left(\frac{2\pi}{\lambda}\Delta\ell\right)\right]. \quad (1)$$

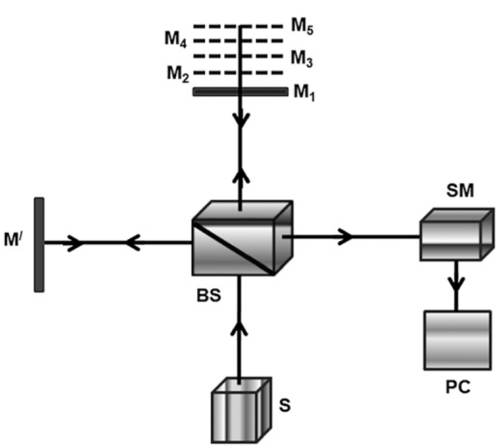

Fig. 1. Schematic of a Michelson interferometer. S is a white light source, M′ is a fixed mirror and the broken lines from M_2 to M_5 represent the positions of the moving mirror M_1 (source spectrum) for red shift, two peak spectrum, blue shift and again source spectrum, respectively. BS is a beam splitter and SM is a fiber-coupled spectrometer interfaced with a personal computer (PC).

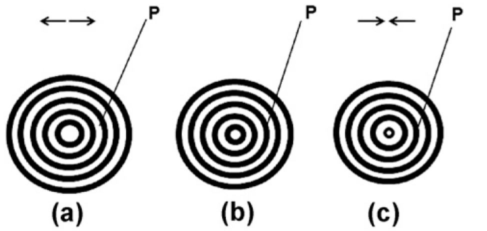

Fig. 2. Change in the position of the observation point P in the interference fringes due to the inward and outward movement of the fringe pattern produced due to the change in the path delay. For M_3 position of the mirror, the fringes are shown in (b) where the point P is at the center of the dark ring. When the path delay is increased, the fringes start moving out and for M_4 position, the point P moves inside (a). For M_2 position, the path delay decreases and as the fringes collapse toward the center, the point P moves outside (c).

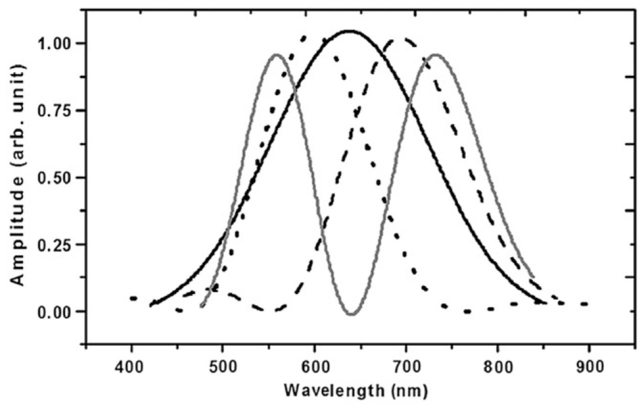

Fig. 3. The spectral shift in the normalized source spectrum for different path delays $\Delta\ell$. Spectrum shown by black line corresponds to the source spectrum for $\Delta\ell \approx 0$. Dashed line shows the red shifted spectrum for $\Delta\ell = 0.78$ μm. The grey line signifies the two peak spectrum for $\Delta\ell = 0.95$ μm and the dots line shows the blue shift for $\Delta\ell = 1.12$ μm.

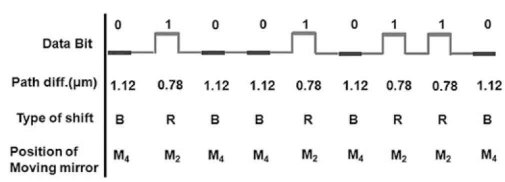

Fig. 4. The data encoding scheme for a bit string 010010110. The bit “1” is associated with red shift and “0” with blue shift of the spectrum. The red shift (R) and blue shift (B) correspond to 0.78 and 1.12 μm path delays in between the interferometer arms, respectively (M_2 and M_4 are being the respective positions of the moving mirror).

Fig. 3 shows normalized values of $S(\lambda)$ for different values of path difference $\Delta\ell$. The theoretical curves clearly indicate the spectral shift (spectral switch) for appropriate path delays. The use of a collimator with the white light source gives straight interference fringes along with the spectral switch in the vicinity of dark fringe.

3. Scheme for data encoding

For the purpose of data encoding, the data is taken in the digital form, i.e. in bits. Taking the two-peak spectrum as a reference, the shift towards one end of the spectrum if is associated with a bit of information say “1”, the shift in the other

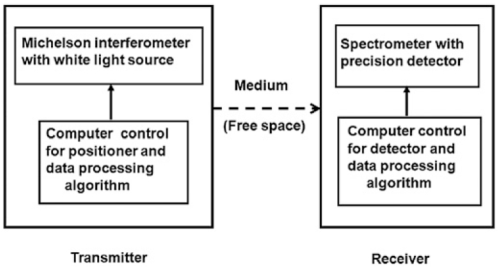

Fig. 5. The free space communication scheme for the encoded data. This simplex network contains a transmitter consisting of a white light interferometer and computer-controlled positioner along with the algorithm to transmit the shifted spectrum. At the receiver end, a fiber-coupled, high-resolution spectrometer is used with competent computer algorithm.

direction will be associated with bit "0". For example, let the data to be encoded is 010010110. As shown in Fig. 4, each bit "0" and "1" could be associated with blue shift and red shift, respectively. However, it is not customary and can be otherwise also. For blue shift, the moving mirror will take M_4 position (refer to Fig. 1). The position M_2 will be occupied by the mirror for the red shift. Thus the whole data could be encoded accordingly (Fig. 4).

It is worthwhile to mention that the path delay is not well specified for any kind of spectral shift. The user can choose any arbitrary value, out of the possible values for that shift. For example for red shift, the path delay could have any value between 0.70 and 0.80 μm. In the same manner, for blue shift the path delay can be assigned any value between 1.10 and 1.20 μm.

4. Data transmission method

For transmitting the data encoded using the above-mentioned mechanism, a communication system could be designed (Fig. 5). The self-similarity of the far-zone spectrum [15] makes it possible to transmit the information over appreciable distances. The system similar to the other conventional ones consists of two ends, i.e. transmitter and receiver. The simplex, i.e. only one way communication, is taken into account. The transmitter consists of a Michelson interferometer with a high intensity white light source. The path delay is introduced by moving the mirror using motorized nano-positioner. The data to be transmitted may be entered in any of the specified languages. The computerized system will convert this data into machine language, i.e. a series of 0 and 1s. The system will take the data sequentially and the computer algorithm will determine the movement of the mirror for the specified value of the data, i.e. 0 or 1. Once the data bit is associated with the predefined spectral shift, it is transmitted to the receiver through free space.

At the receiver end, a computer-controlled fiber-coupled spectrometer with competent algorithm could be used. The system would be pre-aligned with the transmitter and the fiber tip locates the observation point at the fringe pattern. The transmitted spectra from the transmitter could be measured by the spectrometer. A predefined time delay between successive data bits could separate the spectral shifts from one another. To make the system more accurate, acknowledgement methods with error detection and correction algorithms could be implemented.

5. Comparison with existing schemes: advantages and limitations

In the Pulse Code Modulation (PCM) scheme of digital communication the data of any language is first converted into a series of 0's and 1's and then each bit of data is transmitted in the form of a well-shaped pulse of appropriate voltage level. It is received at the receiver end and gets converted into the data bit according to the voltage level. In this scheme at the receiver end if by any chance the incoming pulse becomes distorted (due to noise) and the voltage level for 1 bit changes to voltage level for 0 bit, the whole data becomes useless. In spectral switches based data transmission, the 0 and 1 bit, on the other hand, correspond to either red or blue shift, i.e. an appropriate frequency level. As the noise affects the amplitude of the signal, the proposed system being frequency dependent, remains immune to noise. The receiver, being a sensitive spectrometer reads the spectral shift only and thus shows less affinity to noise.

In Refs. [12,15], the spectral switch is obtained either by modulating the spatial coherence of the source or by changing the diffraction angle. However, in temporal coherence-based spectral anomalies, spectral switch is achieved by changing the position of the moving mirror along the direction of the beam. The advantages of later method used to produce spectral switches for data encoding and free space communication are as follows.

1. The interference fringes obtained in a temporal coherence-based system (Michelson interferometer) are sharp as compared with those obtained in a spatial coherence-based system (Young's apparatus).
2. Making use of precision linear stage for mirror, the switching phenomena in a temporal coherence-based system could be obtained much conveniently. One has to move the variable mirror only by a known amount along the beam direction.
3. The loss of light in the final measurement could be minimized using high-quality optics (mirrors, beam-splitters, etc.) and making the system more compact. In spatial coherence-based systems, the partial coherence is obtained by van-Cittert Zernike theorem, in which a compromise between intensity and visibility of the fringes is unavoidable.
4. Making use of a broadband interference filter, the temporal coherence of the source could be increased. This might provide ease in obtaining the fringe pattern by increasing the sharpness of fringes.
5. Using fiber-coupled devices (source, detector) high throughput of light and secure communication could be achieved.

The proposed system might be efficient for data encoding, data communication and noise reduction; however, complex in its realization. The alignment of optics, the resolution and sensitivity of the detector, high precision of nano-positioner and competency of the algorithm are the key issues that need technical sophistication and expertise. Unfortunately, the mechanical aspects compromises with the speed of the system and make it slow compared to its electronic counterparts. Moreover, the system being raw, the data security, information hiding and cryptography issues are to be addressed. The information hiding and cryptography aspects could be taken into account to develop it for commercial and strategic purposes. More research is needed to resolve the intricacies of the system to make it fast, cost effective and easy to realize. Although diffraction-induced spectral anomalies have been investigated for more than a decade and numerous applications have been proposed but in the perspective of data encoding and data transmission, temporal coherence-based spectral anomalies might win the race.

6. Conclusion

In conclusion, we have proposed a method for information encoding using the spectral anomalies due to temporal correlation in a white light interferometer. Its potential application in data transmission is also discussed. It is shown that by proper choice of path delays between the two arms of the Michelson interferometer, the spectrum at the observation point could be red shifted or blue shifted associating the data bit "1" or "0", respectively. This encoding scheme is investigated for free space communication using a simple communication network model. The present method is further analysed describing its advantages and limitations over its peers.

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