Observation, Generation and Application of New Phenomena Associated with the Spatial Distribution of the Wave Characteristics of Light (Amplitude, Phase, and Polarization State)

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Summary of Research

Generation, Measurement, and Application of Laguerre-Gaussian Beams

Information and communication technologies using light can be found in every corner of our daily lives, ranging from high-speed Internet delivered through optical fibers to CD and DVD drives that use laser beams to read and write information. While light is a common factor in all these applications, it is utilized in different ways; light can be modulated in various forms or shaped into nanoscale profiles to suit the specific application.

Among these various forms of light, the Laguerre-Gaussian (LG) beams are unique and offer a broad range of applications. An LG beam is a laser beam to which a “twist” has been imparted, a form of light that rotates around the beam axis as it propagates through space.

Characteristics of LG Beams

A typical laser beam is brightest at the center and has nearly flat wavefronts. In contrast, an LG beam is dark at the center and has a wavefront resembling a spiral staircase. It rotates around the beam axis as it extends in the direction in which the beam travels. If you observe the electric and the magnetic fields while making a full rotation in a plane perpendicular to the axis of propagation, you will see that both fields go through *m* number of oscillations and return to their original state. By “twisting” the light in exactly this manner, a stable vortex associated with an integer *m* is created, producing a truly unique form of light.

This beam has the ability to transfer its rotation to an object through which it passes. Absorption is one mechanism for transferring rotation; another occurs when the magnitude of the rotation of the beam (integer *m* discussed above) is changed by the shape of the object. In both cases, the difference in the rotation of the light as it enters and leaves the object is transferred to the object. This property of the LG beam allows us to create optically-driven micromotors.

Using LG Beams in Quantum Communication

LG beams can also be applied to quantum information technologies such as quantum computing and quantum cryptography. The quantum bit (qubit), the smallest unit of information in quantum computing, takes the value of 0 or 1, or a superposition of both. In contrast, by utilizing the property of LG beams that a stable vortex corresponds to an integer *m*, we can express the values 0, +1, -1, etc. or superpositions of such, allowing us to send more information per photon.

Conventional quantum communication based on qubits can work well when transmission is stable, but corrections become necessary when noise comes into play. One proposal suggests that when this correction is taken into account, it may be better to bundle information in larger units, sending signals using three states such as 0, +1, and -1. Due to this, the potential of LG beams as carriers of quantum information is attracting attention.

Research at our laboratory is currently focusing on generating and precisely measuring LG beams, as well as exploring potential applications.

Keywords

Laguerre-Gaussian beam (LG beam), light wave, phase, polarization, amplitude, rotation, phase distribution, photon, hologram, quantum computer, quantum mechanics, quantum information, quantum communication, real-time measurement of 3-dimensional object shape, fringe image, quantum bit

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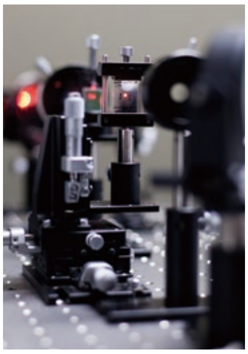
Advantages

Ability to Switch Between Different Beam Shaping Methods Using Two Types of Holograms

LG beams are typically generated by shaping light with computer-generated holograms. Microfabrication of polymers by electron beams or liquid crystal devices are used to create phase modulation patterns, and the light is shaped by passing through this pattern.



Microfabricated hologram

At our laboratory, we do not outsource polymer microfabrication processes. We perform them ourselves using the semiconductor microfabrication facilities at the Satellite Venture Business Laboratory (SVBL) of the University of Electro-Communications, which supports research targeting business venture generation. We use an electron beam writer in the SVBL cleanroom to create holograms capable of generating unique light waves with helical phase structure. The ability to create the holograms on our own lets us make delicate modifications in a flexible manner. This is a major strength because few research groups working on LG beams have access to such capabilities.

Adjusting optical systems

A method recently developed does not require such esoteric facilities. The method is extremely simple, requiring only the connection of a liquid crystal holographic instrument to a PC to form the beam generation hologram. Our laboratory uses this method as well.

The phase of the LG beam produced by the hologram is not always the same as that simulated on the PC. The liquid crystal device technique allows easy modification of the holograms. But while the electron beam writer at the SVBL semiconductor processing facility can produce ultra-precise holograms at resolutions of 10,000 × 10,000 pixels, the maximum resolution achievable with the liquid crystal device technique is about 1,000 × 2,000. Our ability to use both methods and select the method most suitable for a particular case is yet another advantage.

Precision Phase Measurement with the Fourier Transform Method

Another major advantage is access to the Fourier transform method developed by the Takeda Laboratory at our university to precisely extract phase information from a fringe pattern. This method allows the extraction of the shape of an object or the phase distribution of light from the distortion of a fringe pattern projected onto an object or an interferometric fringe pattern recorded with an interferometer. Our laboratory is developing a high-speed real-time 3D shape measurement system based on this technique. The method can also be applied to LG beams generated by the hologram to assess the accuracy of phase modulation, making it possible to make wavefronts of even higher precision.

Typically, an LG beam is regarded to have been successfully generated when a branched interference pattern appears when the beam is made to interfere with a beam having a flat wavefront. At our laboratory, we confirm beam generation success by determining the precise phase distribution by applying a Fourier transform to the interference pattern image, extracting the necessary components, and executing an inverse transform. The precise measurement of the phase distribution allows us to create a more accurate wavefront. LG beams with accurate wavefronts will not only be accurate in phase but also have an ideal axially symmetric brightness distribution, and the transfer of rotation to objects will also be more smooth. Correspondence with integer *m* will also be clearer, and make information transmission more precise.

Future Prospects

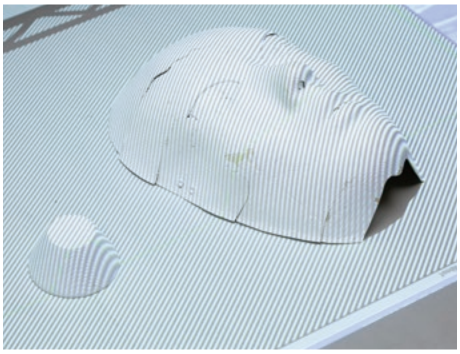
Controlling the Phase of Light to Create the LG Beam of Ultimate Beauty

Phase is a key factor in the study of the spatial distribution of light. More precise phase control of light translates into higher quality LG beams. The goal of our laboratory is to generate LG beams of ultimate beauty and having a large rotation.

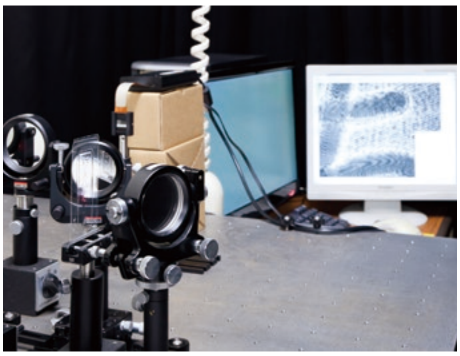
In the past, our only choice was to patiently repeat the polymer hologram microfabrication process. With the advent of the new liquid crystal hologram device, we can now freely generate the phase distribution desired. This system is being gradually improved to offer better phase modulation precision and an increase in the number of pixels it can handle, freeing us from the worries of hologram fabrication and letting us focus on developing applications for the generated beam. In addition to the LG beams, we are also interested in tackling the challenge of generating and manipulating new types of light offering new capabilities.

One challenge is to develop a technique to control the spatial distribution of polarization, the remaining degree of freedom of a light wave besides amplitude and phase. The polarization state of light describes the tendency of light waves to oscillate in a specific direction. It is useful in characterizing materials with specific orientations such as crystals, and for inspecting distortions and stresses that accumulate in an object being worked during a manufacturing process.

An element capable of generating light that exhibits a distinctive spatial distribution can be used as a filter to select and detect components of light that have a corresponding spatial distribution. An interesting task for the future might involve combining an illumination with distinctive spatial distribution with a filter to efficiently examine object shapes or material characteristics, or devising a new information processing mechanism that uses the spatial distribution of light.



Measuring height variation by fringe image projection



Measuring the shape of transparent objects