HIGH-SPEED TRANSMISSION OF IMAGES WITH LIMITED DIFFRACTION BEAMS

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INTRODUCTION

Limited diffraction beams have a large depth of field.[1] They could have applications in medical imaging,[2] tissue characterization,[3] volumetric imaging,[4] estimation of transverse velocity of blood flow,[5] nondestructive evaluation (NDE) of materials,[6] 2D and 3D high frame rate imaging with simple hardware,[5,7–8] as well as other physics related areas such as electromagnetics[9] and optics.[10]

In this presentation, limited diffraction beams are used as carriers to transfer signals in parallel over a large distance.

PRINCIPLE

Limited diffraction beams are exact solutions of the isotropic-homogeneous scalar wave equation. Because the equation is linear, a linear superposition of these beams of different parameters can form a composite beam that is also a solution.[11] Therefore, according to the Huygens Principle, the composite beam can be produced with a planar wave source such as an acoustic transducer, electromagnetic antenna, or a laser device.[12]

Theoretically, limited diffraction beams can propagate to an infinite distance without changing their shapes if they are produced with an infinite aperture and energy. In practice, the aperture is always finite. In this case, limited diffraction beams have a finite but large depth of field, i.e., they can propagate to a large distance without significant distortion.[13,14] For example, if the diameter of an antenna is 20 m and the Axicon angle of an X wave is 0.005° or smaller, the minimum depth of field is about 115 km or is determined by the Rayleigh distance, whichever is smaller.[13] In addition, limited diffraction beams of different parameters are orthogonal to each other and thus they can be separated when received.[11] This means that limited diffraction beams can be used to carry multiple signals simultaneously over a large distance for wireless telecommunications.

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The principle of a telecommunication system using limited diffraction beams is shown in Figure 1. To transfer multiple images in parallel, the images are digitized and then binary encoded. The binary codes are used to modulate (turn on/off) the transmissions of multiple limited diffraction beams of different parameters. The modulated beams are linearly superposed to form a hybrid beam that is transmitted with a physical device. After propagating over a large distance (within the minimum depth of field of the beams), the hybrid beam is received. In the receiver, limited diffraction beams are separated according to their parameters. Multiple binary signals are then detected and decoded to recover the original images simultaneously.

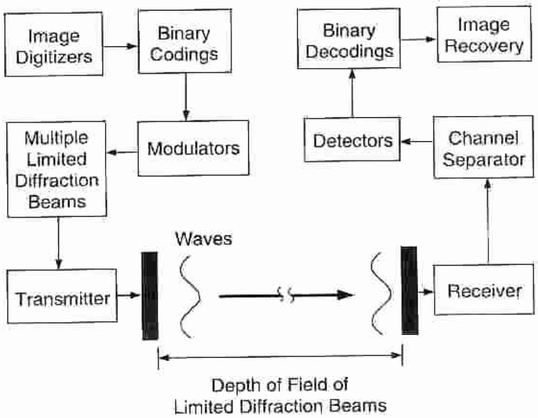

Figure 1. A schematic for parallel transmissions of binary signals with limited diffraction beams.

METHOD

Many types of limited diffraction beams such as Bessel beams,[10] X waves,[13,14] and array beams[4,5,11] can be used to transfer signals. For each type of beam, parameters such as initial phases, orders of the beams, scaling parameters, or Axicon angles, etc. can be used to distinguish beams.[15,16] For simplicity, in the following, zeroth-order acoustic X waves of different Axicon angles are used to demonstrate the principle of the method.[13,17]

To produce a modulated X wave, a ring transducer is placed at the focal plane of a lens (Figure 2). The ring is excited with a signal that is modulated with binary codes that represent a desired image. The acoustic field produced immediately after the lens is approximately the Fourier transform of the wave produced by the ring, which is an X wave. The Axicon angle of the X wave is given by[12,13] $\zeta = \sin^{-1}(a_r/F)$, where a_r and F are the radius of the ring and the focal length of the lens, respectively. The aperture size[13] of the X wave is determined by the diameter of the lens, D. The depth of field[13] of the X wave is given by $XZ_{max} = (D/2)\cot\zeta$.

To produce two X waves of different Axicon angles, two rings must be used. If the two rings are excited simultaneously, a hybrid wave that is a linear superposition of the X waves produced by individual rings is obtained. The hybrid wave can carry multiple signals and propagate to a remote receiver (Figure 3). In the receiver, another lens is used to decompose the hybrid wave back into a ring field at its focal plane corresponding to the Axicon angles of the waves.[12,13] Binary signals are then received with ring detectors and images are recovered simultaneously.

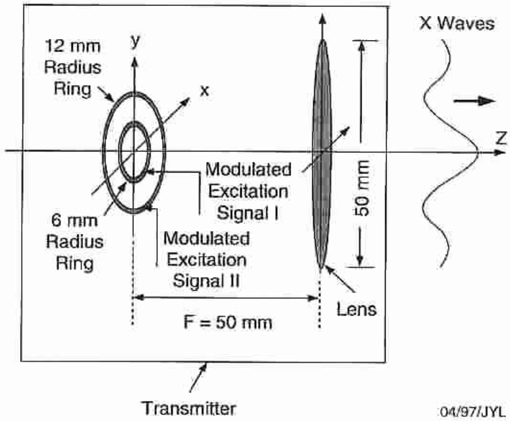

Figure 2. A transmitter system that produces multiple X waves of different parameters (Axicon angles). Both the focal length and the diameter of the lens are 50 mm. Radii of the inner and outer rings are 6 and 12 mm, respectively.

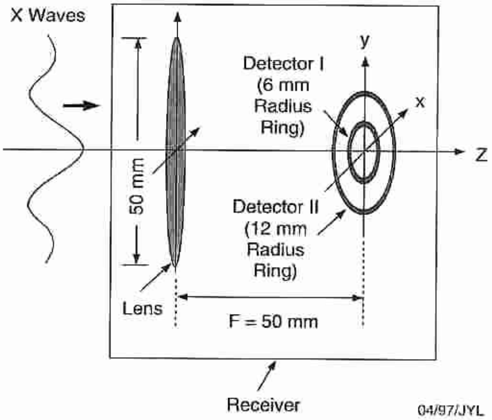

Figure 3. A receiver system that decomposes X waves of different parameters (Axicon angles) back into ring field for detections. For simplicity, the parameters of the lens are chosen the same as those shown in Figure 2.

RESULTS

The X waves produced with the lens of the transmitter in Figure 2 are shown in Figure 4 (lower half of the cross section of the axially symmetric X waves).[13] When a binary code is "0" in a signal channel, no X wave is produced from that channel. If the code is "1", an X wave is produced. The bandwidth of the X wave produced is determined by those of the excitation signal and the ring transducer. In Figure 4, X waves produced with a short pulse (1.5 cycles) and with a long tone burst (10 cycles) are shown in the left and right columns, respectively. In acoustic and microwave cases, short pulses can be produced. In optics, tone bursts that are much longer than 10 cycles are usually used. X waves produced with rings that have radii of 6 and 12 mm are shown in the top and middle rows, respectively. Hybrid X waves produced by simultaneous excitations of both rings are shown in the bottom row of Figure 4. In this figure, the center frequency of the wave is assumed to be 2.5 MHz and the diameter of the transmission lens is 50 mm. With these parameters, the depths of field of the X waves are about 206.86 and 101.12 mm for the rings of 6 and 12 mm, respectively, corresponding to Axicon angles of about 6.892° and 13.89°.

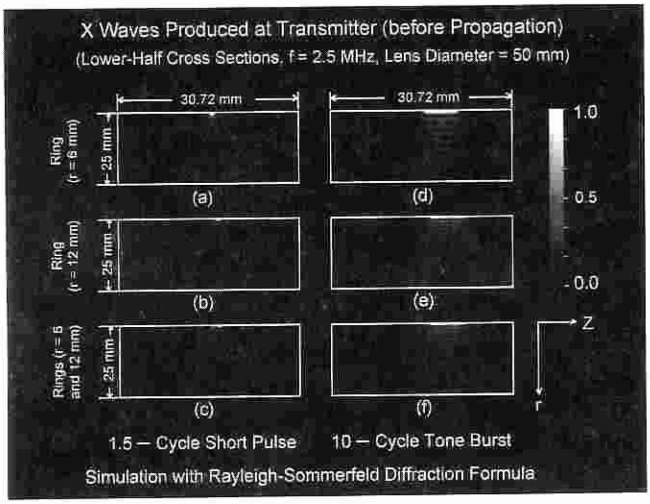

Figure 4. Simulated X waves produced immediately after the transmission lens (see Figure 2). Lower-half of the cross section of the axially symmetric X waves is shown. Panels in the left and right columns are X waves produced with a 1.5–cycle short pulse and a 10–cycle tone burst, respectively. Panels in the top and middle rows are X waves produced with rings of 6 and 12 mm radius, respectively. Panels in the bottom row are a hybrid wave produced when both rings are excited. The Rayleigh-Sommerfeld diffraction formula is used in the simulation. A Blackman window function centered at 2.5 MHz with a relative bandwidth of 81% of the center frequency is assumed. Analytic envelopes of the waves are displayed.

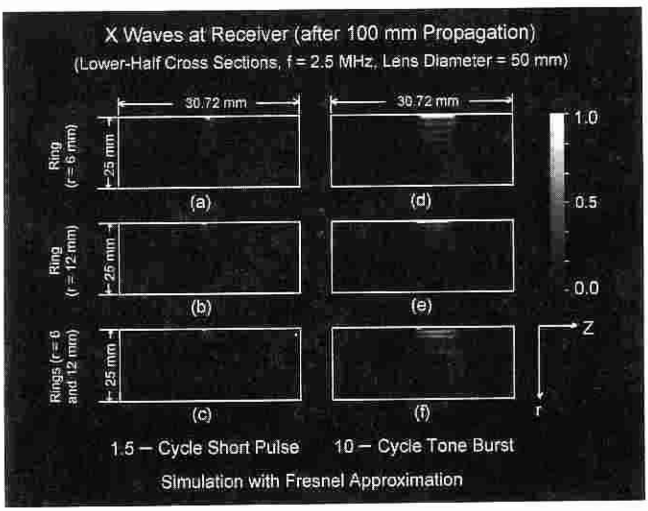

Figure 5. Simulated X waves after propagating over 100 mm. The layout of this figure is the same as that of Figure 4. The Fresnel approximation is used in the simulation.

After propagating over 100 mm, which is approximately the minimum depth of field of the X waves, the results are shown in Figure 5. It is seen that the distortions of X waves are small.

From the X waves shown in Figure 5, ring fields are recovered at the focal plane of another lens (Figure 6). Ring detectors are placed at peaks of the ring field corresponding to the transmit rings in Figure 2 to receive the binary signals and recover images simultaneously. It is seen that the rings are reconstructed very well. From Figure 6, it is clear that more transmit rings and detectors can be added to increase the number of channels of the communication system.

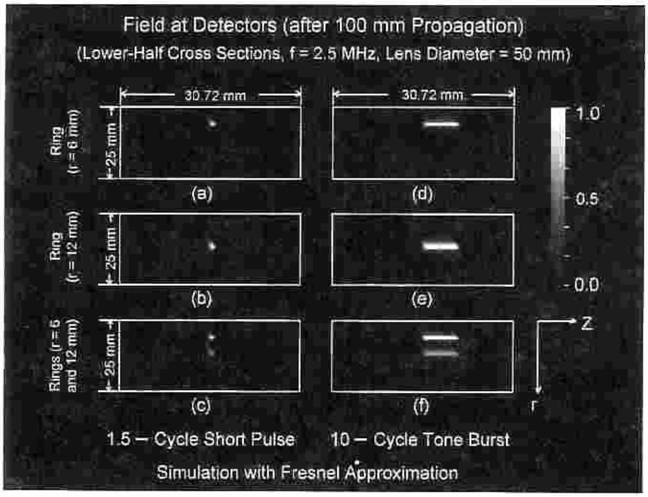

Figure 6. Simulated acoustic fields at the focal plane of the reception lens produced by X waves of different parameters. The layout of this figure is the same as that of Figure 4. The simulation is carried out with the Fresnel approximation.

DISCUSSION

It should be noticed that the method proposed in this paper is only suitable for near-field communication, i.e., within a large depth of field of limited diffraction beams (Figures 4 and 5). Because limited diffraction beams are highly collimated in the near field, this method may be useful for a high-speed wireless private communication. In addition, the collimated beams do not have the problem of multiple reflections from surrounding objects.

In Figure 3, the ring detectors used are phase sensitive. This requires that the transmit rings, lenses, and the ring detectors in Figures 2 and 3 to be coaxially aligned and perpendicular to the beam axis to avoid phase cancellation and thus to increase signal-to-noise ratio. Because of the phase sensitivity, background noise from random radiation sources will be largely cancelled.

From Figure 6, it is seen that the ring fields reconstructed from the X waves have a certain width that increases with the decrease of the diameter of the reception lens. In addition, sidelobes of the ring fields will increase the effective ring width. A larger width will reduce the number of rings that can be placed in the system. The number of rings will also be reduced if the communication distance is increased. This is because a larger distance decreases the largest diameter of the rings.

It is worth noting that array beams[4,6–8,11] can also be used in the communication system. In this case, point sources and detectors are used to replace rings. This will greatly increase the number of channels. However, the signal-to-noise ratio may be reduced because the transmitter and detector sizes will be small and the detectors will be phase insensitive.

CONCLUSION

A method for parallel transmissions of digital binary signals with limited diffraction beams such as X waves has been developed. An acoustic example has been given to demonstrate the method. Because microwave and optic waves obey the same scalar wave equation of the acoustics, the method can also be applied to those areas for high-speed digital wireless telecommunications.

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