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Short Note

Multilevel Phase and Amplitude Modulation Method for Holographic Memories with Programmable Phase Modulator

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The utilization of spatial quadrature amplitude modulation (SQAM) signals with amplitude and phase modulation is a simple method used to improve storage capacity in a holographic data storage system. We propose a multilevel phase and amplitude modulation method for holographic memories with a programmable phase modulator (PPM). In this method, holographic page data is recorded by a two-step exposure process for different phase-modulated data. There is no need to adjust the positions of spatial light modulators (SLM) with high accuracy because we use only one spatial modulator. We estimate the quality of 16 SQAM signals produced by our technique.

Keywords: holographic memory, full complex amplitude modulation, multiplexed hologram

A holographic memory has been focused as a promising technology to realize a large-capacity and high-transfer rate storage. The use of the multilevel phase and amplitude modulated signals for a recording data has recently been proposed.[1–4] The plural information obtained by changing both the amplitude and phase is useful for improving the recording density in the holographic memory markedly.

Several methods for measuring complex amplitude signals have been proposed.[5,6] On the other hand, few practicable methods to generate complex amplitude signals for a holographic memory have been proposed. The simplification, cost reduction of the system design and high-resolution optical data equivalent to a pixel structure on a spatial light modulator (SLM) are important in effective storage systems.

We often use a combination of two types of SLM for the amplitude and phase modulation of the input data because it is difficult to adjust these parameters to arbitrary values simultaneously using a device.[7] In this method, we should adjust the position of the two types of SLM with high accuracy and construct a 4f optical setup. This forms the complex structure of the systems and increases the cost of the system with the two types of SLM.

It is also possible to produce the desired complex amplitude using off-axis computer-generated holograms (CGHs) with a single SLM. In this method, however, it is impossible to attain a high image resolution equivalent to that of a pixel structure on the SLM in principle because the artificial fringe pattern of the CGHs is formed using several pixels of the SLM.

In this paper, we propose a multilevel phase and amplitude modulation method for holographic recoding with a programmable phase modulator (PPM). Two spatial phase page data are multiplexed in the same position using the same reference beam as sub holograms, where a multiplexed sub hologram is equivalent to a hologram for generating the desired multilevel complex amplitude signals. The resolution of the reconstructed signal is equal to that of the SLM. The method enables simple construction of the storage system and results in high cost performance using only a spatial phase modulator. We estimate the quality of 16 SQAM signals produced by our technique.

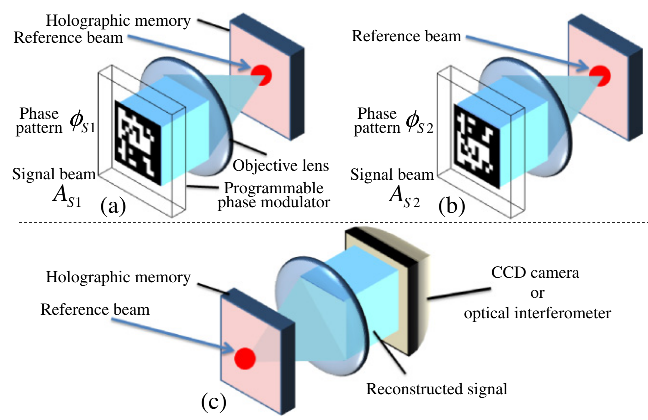

Fig. 1. (Color online) Recording and reading processes for multilevel phase and amplitude modulation with PPM: (a) (b) recording process, and (c) reading process.

Figure 1 shows the optical setup for multilevel phase and amplitude modulation with a PPM. The hologram for a complex amplitude signal is recorded by a two-step exposure process. In the first step, the sub hologram is written by the reference beam and the signal beam A_{S1} whose phase distribution ϕ_{S1} is given to the signal beam by the PPM as shown in Fig. 1(a). The complex amplitude of the signal is given by

$$A_{S1} = \sqrt{I_{S1}}\exp(j\phi_{S1})\exp(-j\mathbf{k}_S\cdot\mathbf{r}), \tag{1}$$

where I_{S1} is the intensity of the signal, $\mathbf{k}_S$ the wave number vector, and $\mathbf{r}$ the positional vector.

In the second step, we also multiplex the next sub hologram at the same position by the same reference beam and the signal beam A_{S2} whose phase distribution is ϕ_{S2} as shown in Fig. 1(b). The signal beam A_{S2} is given by

$$A_{S2} = \sqrt{I_{S2}}\exp(j\phi_{S2})\exp(-j\mathbf{k}_S\cdot\mathbf{r}), \tag{2}$$

where I_{S2} is the intensity of the second signal beam. Note that the signal beams A_{S1} and A_{S2} have a uniform intensity

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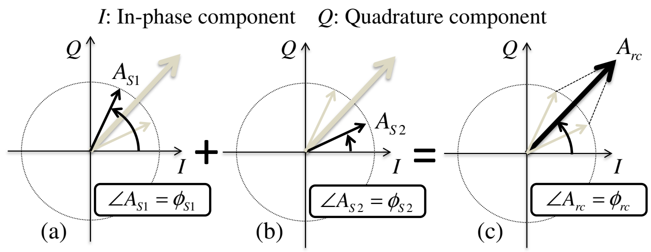

Fig. 2. (Color online) Relationship between recording beams and reconstructed beam: (a) complex amplitude A_{S1} (b) complex amplitude A_{S2} and (c) summation of two complex amplitudes A_{rc}.

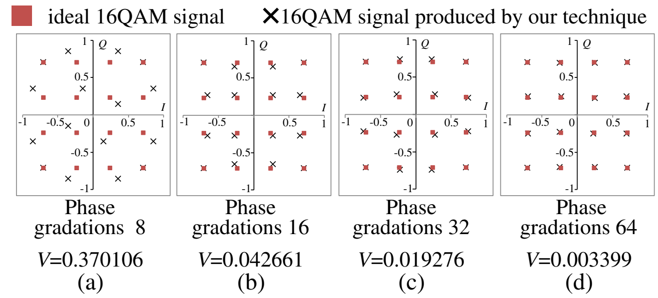

Fig. 3. (Color online) Comparison of ideal SQAM signals with signals produced by two-step exposure process.

distribution. The recording time is adjusted to equalize the modulation depths of the two sub holograms.

In the reading process, the reference beam is input to the hologram as shown in Fig. 1(c). The reconstructed signal A_{rc} to the optical interferometer can be regarded as the composite wave of the beams:

$$A_{rc} \propto A_{S1} + A_{S2}, \tag{3}$$

where the first and second terms correspond to the beams diffracted by the first and second sub holograms, respectively. Under the assumption that the diffraction efficiencies of the two sub holograms are the same, Eq. (3) is rewritten as

$$A_{rc} = \sqrt{I_S}\exp(j\phi_{S1}) + \sqrt{I_S}\exp(j\phi_{S2}), \tag{4}$$

where I_S is the intensity of the diffracted reference beam. The relationship between the recording beams and the reconstructed beam is shown in Fig. 2. The phase and amplitude are derived as

$$\phi_{rc} = (\phi_{S1} + \phi_{S2})/2, \tag{5a}$$

$$|A_{rc}| = 2\sqrt{I_S}\cos[(\phi_{S1} - \phi_{S2})/2]. \tag{5b}$$

It is therefore possible to calculate the optimum phase values of ϕ_{S1} and ϕ_{S2} for the desired complex amplitude A_{rc} whose phase and amplitude are ϕ_{rc} and $|A_{rc}|$, respectively, in the as following equations:

$$\phi_{S1} = \phi_{rc} + \Delta\phi, \tag{6a}$$

$$\phi_{S2} = \phi_{rc} - \Delta\phi, \tag{6b}$$

where $\Delta\phi$ is derived by

$$\Delta\phi = \cos^{-1}(|A_{rc}|/2\sqrt{I_S}). \tag{7}$$

It is possible to recode the optical data having arbitrary spatial complex amplitudes by the two-step exposure process for phase-modulated data corresponding to ϕ_{S1} and ϕ_{S2} in Eqs. (6) and (7).

The degree of accuracy of the produced complex amplitude depends on the number of phase gradations of the PPM. Under the assumption that the numbers of phase gradations are 8, 16, 32, and 64 in the range from 0 to 2π, we produced the 16SQAM signal. We estimated the qualitative performance by the following equation:

$$V = \sum_{n=1}^{16} ||A_{in}|\exp(j\phi_{in}) - |A_{rcn}|\exp(j\phi_{rcn})|^2, \tag{8}$$

where n denotes the symbol number. A_i and ϕ_i are the ideal amplitude and phase values of 16SQAM, respectively. A_{rc} and ϕ_{rc} are also the amplitude and phase values produced by the two-step method using the PPM, respectively. In the simulation result, we assumed that the maximum values of $|A_i|$ and $|A_{rc}|$ are equal to 1.0.

Figure 3 shows the ideal and produced 16SQAM signals. This figure also indicates the values of V relative to the number of phase gradations. We found that the accuracy of the produced complex amplitude improves as the number of phase graduations of the PPM increases. Under the assumption that the number of phase gradations of the PPM is 2^m in the phase range from 0 to 2π, the number of reconstructed amplitude gradations with a constant phase value is equal to $2^{m-2} + 1$. The number of phase gradations in the actual phase modulator is more than 200. It is therefore possible to produce a sufficiently high accuracy SQAM signal for practical use in a holographic memory. Furthermore, the resolution of the reconstructed complex amplitude data is equivalent to that of the SLM.

In this paper, the reconstructed wave is regarded as the composite wave of the beams diffracted by the two sub holograms. In the actual recording process, the refractive index distribution produced by multiplexing sub holograms is complex because the second signal and reference beam are diffracted by the first sub hologram in the multiplexing process for the second sub hologram. We plan to investigate the procedure process for the three-dimensional index distribution by numerical simulation based on the beam propagation method and to estimate the quality of the SQAM signals produced by our technique.

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