Proximity Effect on Nanophotonic Phased Arrays

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Abstract: Proximity effect can affect thermal-modulated nanophotonic phased array holographic displays. The impact of proximity effect on holographic imagery is investigated and the improvement using proximity effect correction methods is demonstrated.

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1. Introduction

The successful display of desired 2D or 3D imagery on nanophotonic phased arrays (NPA) requires precise and independent control of the phase of the pixels. For thermal-modulated NPAs, one type of error is due to the proximity effect, which is the phenomenon where a pixel's heat affects its surrounding pixels. The proximity effect contributes to the degradation of the observed image and must be taken into consideration.

In our case of NPA holographic displays, the proximity effect can be modeled as a convolution, written as $\hat{T} = T * K$, where T is the input temperature profile, and $\hat{T}$ is the resulting temperature profile on the device. K is the thermal spread kernel and $*$ represents the convolution.

In this study, we investigate the extent to which proximity effect affects the image formed on NPA holographic displays and demonstrate how proximity effect correction (PEC) methods can improve the formed images.

2. NPA Holographic Display

Fig. 1 (a) shows the schematics of the NPA we have developed. Each array unit consists of a tunable thermo-optical phase shifter that is coupled into an optical antenna. The power is evenly distributed into each pixel by accurately designing the directional couplers. The phase of the NPA holographic display pixels is modulated with the temperature, and an IC chip is flip-bonded to control the temperature of each pixel. The relationship between the phase P_i of a pixel i and its temperature T_i (above room temperature) is $P_i(T_i) = \gamma T_i$. Note that T_i must be non-negative for physical plausibility. From the simulations run on our sample device, γ is inferred to be $\frac{\pi}{175}$.

To quantify the proximity effect, simulation is done on a 5×5 array where the center pixel is supplied with power and the temperature on all pixels is measured. Using the measurement, we model thermal proximity effect as $T_{i \to j} = T_i \exp(-d(i,j)^2/\sigma^2)$, where $T_{i \to j}$ refers to the temperature rise in pixel j caused by pixel i, T_i is the temperature of pixel i before proximity effect and $d(i,j)$ is the distance between pixels i and j measured in pixels (px). We can construct the thermal spread kernel K with $\sigma = 0.66\ px$ derived from the simulation result.

3. Simulations

We perform a series of simulations to find out how the proximity effect can affect the quality of NPA holograms. In the simulations, we use Fourier holograms. After the phase is adjusted in the near field to simulate the proximity effect and the PEC methods, we use its Fourier transform to simulate the observed far-field image. In this study, we only consider the phase signals of the hologram and assume perfect amplitude signals.

First, we quantify the impact of proximity effect and its correction as the average difference $D_K(T)$ between the desired phase temperature profile $\tilde{T}$ and the phase temperature profile $\hat{T}$ we can expect to achieve on the NPA. $D_K(T)^2 = \frac{1}{N}||\hat{T} - \tilde{T}||_F^2$, where $||\hat{T} - \tilde{T}||_F$ is the Frobenius norm and N is the total number of entries in $\hat{T}$ or $\tilde{T}$.

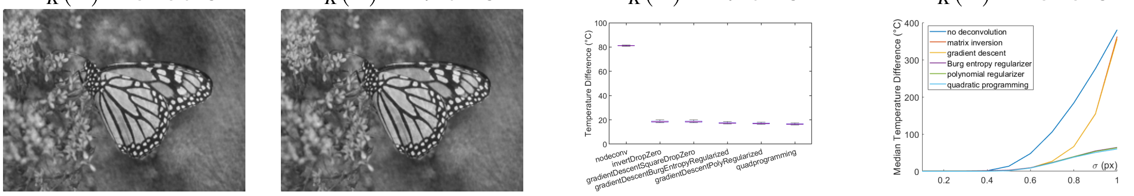
Next, we establish a relationship between $D_K(T)$ and the observed image quality measured with *structural similarity index* (SSIM) [1]. This can be seen in Fig. 1 (b), where image quality degrades as $D_K(T)$ increases.

We use several PEC methods. The first is the matrix inversion method. The thermal spread convolution can be written into a matrix multiplication form $v_{\hat{T}} = M_K \times v_T$, where v_T is the vector form of the temperature profile T. If M_K is nonsingular, matrix inversion can give a unique solution. We can also use linear programming to minimize $D_K(T)$, with the cost function being $f(v_T) = ||v_{\tilde{T}} - M_K \times v_T||_2^2$. These methods can produce negative entries in the solution. One method to address this problem is by setting the negative entries to zero [2], which is used in the

(a) NPA circuit (b) SSIM vs $D_K(T)$ (c) $D_K(T) = 0$°C, SSIM=1 (d) $D_K(T) = 40$°C, SSIM=0.62

Fig. 1. NPA circuit and relationship between image quality SSIM and $D_K(T)$. Larger temperature difference leads to more degraded images.

no deconvolution $D_K(T) = 81.50°C$ | matrix inversion $D_K(T) = 19.61°C$ | gradient descent $D_K(T) = 19.61°C$ | Burg entropy regularizer $D_K(T) = 18.23°C$



polynomial regularizer $D_K(T) = 17.86°C$ | quadratic programming $D_K(T) = 17.32°C$ | PEC methods on 29 images | Median $D_K(T)$ vs σ

Fig. 2. Simulated results of proximity effect and its correction

matrix inversion and gradient descent methods shown in Fig. 2. Alternatively, we can add a regularizer term to the cost function to penalize the solution approaching zero. Two such regularizers are $r(v_T) = \sum_i -\beta \ln(v_{T\,i})$ based on Burg entropy and a polynomial regularizer $r(v_T) = \sum_i {v_{T\,i}}^{-\alpha}$, whose results are also shown in Fig. 2. Finally, we use quadratic programming as the best case by minimizing $f(v_T)$ while requiring v_T to be non-negative. Examples and the box chart of simulation results with $\sigma = 0.66$ on 29 images are shown in Fig. 2.

Lastly, simulation results with different thermal spreads σ are shown at the bottom right of Fig. 2.

4. Conclusion

In this study, we show that the thermal proximity effect reduces the far field image quality on NPA holographic displays. PEC methods can improve image quality, and those with non-negative constraints are more resistant to larger thermal spread σ than others. While quadratic programming produces the smallest temperature difference and can be considered to be the best, the $D_K(T)$ difference among the five PEC methods is not significant. The matrix inversion method takes significantly less time than all the other methods and offers a good trade-off between quality and processing time. But this is only true when σ is small with respect to the pixel pitch. When inter-pixel thermal "cross talk" is large, matrix inversion breaks down as a viable method of proximity control.

Furthermore, we can use the results from this study to help determine the pixel pitch of the NPAs. Smaller pixel pitch could lead to larger thermal spread σ. Based on our sample device and simulations, we can achieve 9.36 µm pixel pitch if we use a PEC method to compensate for the proximity effect to achieve an SSIM larger than 0.7, as opposed to a pixel pitch of 14.06 µm if no PEC method is used.

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