Study on a method of evaluating the alignment of pixels between fiber-optic image bundles and detector arrays

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An evaluating method is proposed for aligning fiber-optic image bundles finely to detector arrays with coupled contrast transfer function (CTF). The mathematical expression of coupled CTF is deduced based on the definition of the CTF. The paper discusses the characteristics and variation law of coupled CTF at the *Nyquist* frequency domain. The results show that the value of coupled CTF is closely related with aligning accuracy. According to the value of coupled CTF, it can accurately determine the situation of aligning between fiber-optic image bundles and detector pixels. Accordingly, this paper proposes a new method to evaluate the aligning accuracy between fiber-optic image bundles and detector pixels using the coupled CTF. © 2011 Optical Society of America

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1. Introduction

The use of fiber-optic image bundles in optical systems can obviously improve their abilities [1,2]. Based on the sampling principle [3,4], the aligning accuracy of pixels between fiber-optic image bundles and detector arrays impacts the imaging quality of the photoelectric imaging system straightly. The way to accurately evaluate the aligning accuracy is basically to precondition the fiber-optic image bundles applied in photoelectric imaging system.

A black and white striped pattern has the advantages of easy preparation and use [5,6]. Currently, many laboratories use the black and white striped pattern to do quality evaluation and assemblage of photoelectric imaging systems [7–9]. Consequently, the paper studied the feasibility of using a black and white striped pattern during the process of aligning a fiber array and detector pixels. The paper established a mathematical model of coupled contrast transfer function (CTF) when fiber image bundles aligned with detector pixels, which was based on the definition of the contrast. Based on the mathematic-physical model, the paper studies the relationship between aligning accuracy of optical-fiber array with the detector pixels and the coupled CTF. We concluded the coupled CTF can evaluate the aligning accuracy between fiber-optic image bundles and detector pixels.

2. Principle and Calculation

Each fiber in fiber-optic image bundles should be one by one aligned to corresponding detector pixels, in a photoelectric imaging system [10,11]. The principle is shown in Fig. 1(a). Actually, the pixels between the fibers and detector array are not fully aligned when there is an absence of an appropriate measurement to determine the real circumstances. This condition is shown in Fig. 1(b).

In Fig. 1, $2r$ and $2R$ refer to the inner and outer diameter of the fiber and $2R \times 2R$ refers to the

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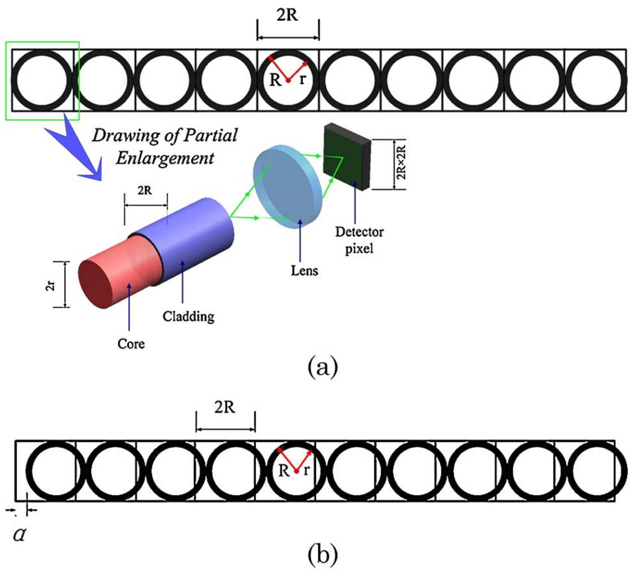


(a)

(b)

Fig. 1. (Color online) Coupled situation between fiber-optic image bundles and the detector pixels. (a) The R is outer radius of fiber in fiber-optic image bundles. (b) The dimension of pixel is $2R \times 2R$, and the alignment error of pixels between fiber-optic image bundles is expressed as α.

size of the detector pixel, where α is the coupling deviation between the pixel and the fiber. The black and white striped pattern (hereinafter referred to as the square wave signal) at f spatial frequency is imaged in the surface of the fiber-optic image bundles. Figure 2 shows the signal transformation processes in this coupled system.

The intensity of the square wave signal sampled by the j-fiber is expressed as follows:

$$I'_j = I_m \cdot \frac{(\pi r^2 - S'_j)}{\pi r^2}, \tag{1}$$

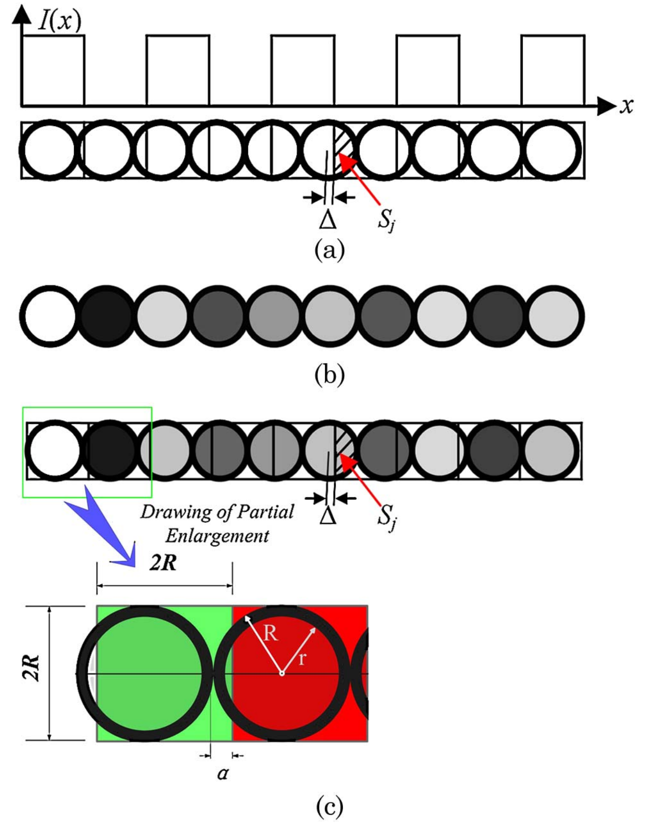
where

$$\begin{aligned} S'_j &= 2\int_{2jR-r+\Delta}^{2jR+r} (r^2 - (x - 2jR)^2)^{1/2} \mathrm{d}x \\ &= r^2 \arccos\left(\frac{\Delta}{r}\right) - \Delta\sqrt{r^2 - \Delta^2} \end{aligned}, \qquad \Delta = \begin{cases} \delta \\ \alpha \end{cases}. \tag{2}$$

The Δ in Eq. (2) express initial positions between the input square wave signal and the fiber-optic image bundles, and the S'_j expresses the shadow area in Fig. 2(a), correspondingly. Moreover, the Δ express alignment error of pixels between fiber-optic image bundles and detector, which result in a secondary modulate with an area of S'_j in Fig. 2(b).

When the transfer loss of single optical-fiber and optical systems is ignored, the signal intensity sampled by the j-pixel of detector can be expressed as

$$I''_j(f, \alpha) = \frac{(\pi r^2 - S_j)}{\pi r^2} I'_j(f) + \frac{S_j}{\pi r^2} I'_{j+1}(f). \tag{3}$$



(a)

(b)

(c)

Fig. 2. (Color online) Sketch of square wave signal transformation. (a) The square wave signal sampled by input side of the fiber-optic image bundles. (b) Signal export from output side of the bundles. (c) Detector pixels sampled the output signal from fiber-optic image bundles.

The square wave signal was output from the detector through the process that sampled by fiber-optic image bundles, transferred by imaging system, and secondarily sampled by detector pixels. Based on this process, the contrast of the output signal can be expressed as follows:

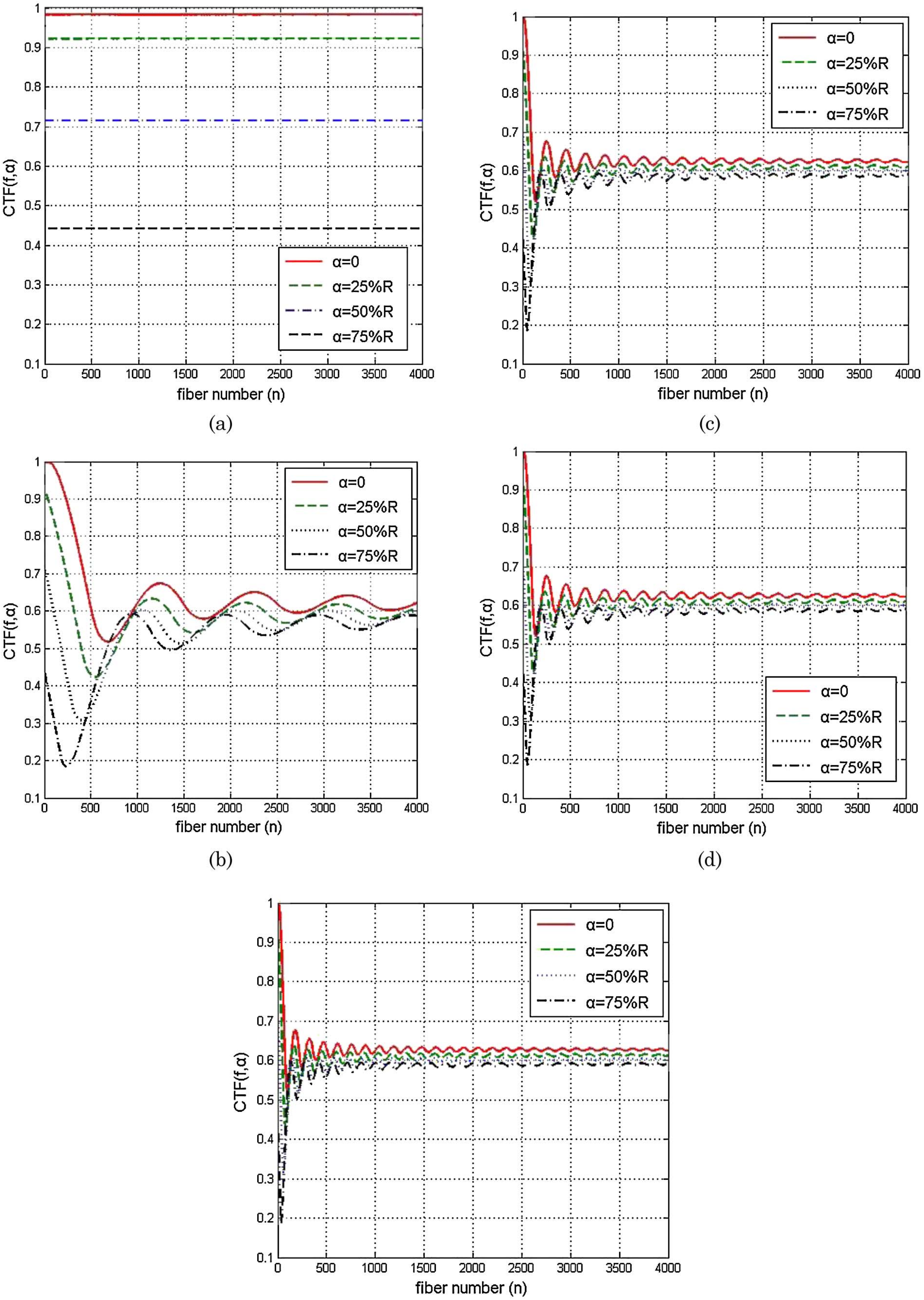
$$C'(f, \alpha) = \frac{\bar{I}''_{\max}(f, \alpha) - \bar{I}''_{\min}(f, \alpha)}{\bar{I}''_{\max}(f, \alpha) + \bar{I}''_{\min}(f, \alpha)}. \tag{4}$$

In Eq. (4) I and $\bar{I}''_{\min}$ are an average value of maximum and minimum of the sampling output from detector pixels, respectively:

$$\begin{cases} \bar{I}''_{\max}(f, \alpha) = \frac{1}{N}\sum_{n=1}^{N} \bar{I}''_{\max n}(f, \alpha), \\ \bar{I}''_{\min}(f, \alpha) = \frac{1}{M}\sum_{m=1}^{M} \bar{I}''_{\min m}(f, \alpha). \end{cases} \tag{5}$$

According to the definition of CTF, the complex photoelectric imaging system consisted of fiber-optic image bundles, optical imaging system, and detector, which coupled CTF expressed as

$$CTF(f, \alpha) = \frac{C'(f)}{C_o(f)}. \tag{6}$$



(a)

(c)

(b)

(d)

(e)

Fig. 3. (Color online) Simulation of the relationship of coupled contrast transfer function with coupling deviation based on Eq. (7): (a) $f = f_N$, (b) $f = 0.999f_N$, (c) $f = 0.997f_N$, (d) $f = 0.995f_N$, (e) $f = 0.993f_N$.

If the contrast of the input square wave signal is $C(f) = 1$ and the CTF of the imaging system is $Co(f) = 1$, then Eq. (7) expresses the coupled CTF in the condition that the aligning error between the pixels and the fibers is in existence. The coupled CTF is derived from Eq. (6) as

$$CTF(f,\alpha) = \frac{\frac{1}{N}\sum_{n=1}^{N} I''_{\max n}(f,\alpha) - \frac{1}{M}\sum_{m=1}^{M} I''_{\min m}(f,\alpha)}{\frac{1}{N}\sum_{n=1}^{N} I''_{\max m}(f,\alpha) + \frac{1}{M}\sum_{m=1}^{M} I''_{\min m}(f,\alpha)}. \tag{7}$$

3. Simulation and Discussion

From Eq. (7), if the condition that frequency of input square wave signal is equal to f_N (*Nyquist* frequency), $0.999f_N$, $0.997f_N$, $0.995f_N$, $0.993f_N$, and coupling deviation α is equal to 0, $25\%R$, $50\%R$, $75\%R$, we calculate and simulate the coupled CTF changed in the situation with a coupling deviation. Moreover, the radius R is equal to $9\,\mu$m, and the radius of the core is equal to $8\,\mu$m in the simulation, which are the actual dimensions of the fiber in the bundles related to the practice applications. The simulation result is shown in Fig. 3. In this figure, the x-axis is the number of fibers in the bundles and the y-axis is the value of the coupled CTF.

From the simulation curve in Fig. 3, we obtain some conclusions as follows. When the aligning error between the fiber-optic image bundles and the detector pixel is in existence and the coupling deviation (α) and frequency of the input square wave signal is fixed, the value of the coupled CTF is a convergent vibration to a fixed value with the increasing of number of fibers. Moreover, the convergent value of the coupled CTF fall with the increasing of aligned deviation.

4. Conclusion

The article starts from the physical process of a square wave signal transfer. Based on the definition of the contrast, we establish the way to evaluate aligning accuracy of pixels between fiber-optic image bundles and a detector array by a physical model of a coupled CTF. In particular, the mathematical expression is deduced.

Based on the mathematical expression, we do the simulation for studying the character of a physical model. From the simulation results, we can get the conclusions as follows. At *Nyquist* frequency domain, when an aligning error between fiber-optic image bundles exists, coupled CTF changes with coupling deviation periodically. If the fiber-optic image bundles are finely aligned with detector pixels, coupled CTF has its maximum value, otherwise in its minimum value. Moreover, the closer the frequency of the input square wave signal to the *Nyquist* frequency, the easier it is to achieve high precise aligning.

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