Demonstration of reconfigurable O-CDMA using liquid crystal modulators

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ABSTRACT

Optical CDMA technology has shown promise in optical communications, particularly in local-area optical fiber networks. We present a novel O-CDMA scheme with programmable and reconfigurable bipolar code capability using liquid crystal (LC) Spatial Light Modulators (SLMs). The key to our system performance depends on constructing a decoder that implements a true bipolar correlation using only unipolar signals and intensity detection. This has been accomplished using two unipolar correlations that can be performed optically, followed by a subtraction. In our coding system, the power spectrum of a broadband light source is encoded and decoded by programming the SLMs. The high polarization selectivity of these components coupled with the polarization rotation ability of liquid crystal elements makes switching possible with high extinction ratio and low crosstalk. Experimental results including the correlation measurements are presented. Good contrast between the autocorrelation and cross correlation values shows that a binary information symbol can be recovered by an appropriate threshold operation.

Keywords: Optical CDMA, LAN, optical communication, liquid crystal, spatial light modulator

1. INTRODUCTION

Recently, optical CDMA technology [1-3] has shown promise in optical communications, particularly in local-area optical fiber networks. O-CDMA technology allows a large number of users to share the entire channel bandwidth of an optical fiber network and offers asynchronous access. This is in contrast to optical TDMA, which has very stringent synchronization requirements. O-CDMA also has an advantage over WDMA, since it eliminates the need for a stable wavelength source and the need for ultrafast tunable sources and filters in future optical packet-switched networks.

In principle, any combination of spatial, temporal, frequency, and polarization information can be used for coding in O-CDMA. There have been several different approaches proposed based on incoherent and coherent techniques. Coherent systems that utilize coherent superposition of fields have been studied by several groups.[1,2] For example, Weiner's group has assembled a simple fiber testbed [4] for an ultrashort pulse code-division multiple-access system, based on encoding and decoding of coherent ultrashort light pulses, in which multiple users share a common fiber medium by using different, minimally interfering optical code sequences. Recently, superstructured fiber-Bragg-grating technology has emerged as an attractive route to produce high-performance optical encoders and decoders.[5,6] But in all cases, ps or fs pulsed lasers and phase detection systems are required, which are generally complex, expensive and cumbersome. Generally, coherent O-CDMA systems also suffer from polarization and phase dependence, which require both polarization control and phase stabilization, and require setting and controlling optical delays on the scale of the optical wavelength in order to achieve the correct phases of superposed fields.

Conversely, incoherent systems based on direct-detection reception, generally lack the bipolarity of coherent systems and are thus not as efficient at rejecting undesired signals in the cross-correlation process.[7] Recently, however, some incoherent schemes implementing bipolar coding, as used in radio frequency CDMA and spread spectrum systems, were demonstrated.[8,9] Young's group [10] implemented a bipolar encoding scheme for coding the power spectrum of an erbium-doped superfluorescent fiber source using passive phase masks. However, the codes are not reconfigurable.

In this paper, we present an incoherent and reconfigurable bipolar coding scheme of broadband light sources using liquid crystal (LC) Spatial Light Modulators (SLMs). The major advantage of this configuration is reconfigurable codes. With high-speed nematic LC such as dual-frequency nematic LC material, the reconfiguration speed can be fast (sub-ms), an advantage for many applications. In addition, the non-uniform spectral intensity distribution of the broadband light source means the coding patterns are not uniform. In principle, the length of the codes could be made longer by encoding more of the spectrum, allowing more users to be supported. This can be done by improving the uniformity of the source spectrum. Alternatively, uniform coding patterns can be obtained by adjusting the intensity of each spectral chip independently via independent adjustment of the driving voltage for each pixel of the SLM, i.e., by using an analog-driven LC SLM. Furthermore, wavelength scale distortion which can be a critical parameter in the correlation process [11] could be corrected actively by using an LC-SLM phase modulator.

2. PRINCIPLES

Figure 1 illustrates the process of data transmission in an O-CDMA scheme. Signals from all transmitters are distributed to every receiver using a star coupler. Each user receives all transmitted information, but is able to extract the signal of one particular transmitter from a background of multi-user interference using prior knowledge of the coding employed. Encoding and decoding processes are performed in the optical domain, eliminating any slowdown associated with optical-electronic conversion required in an electronic-based coding technology, a key motivation behind much of the work in O-CDMA.

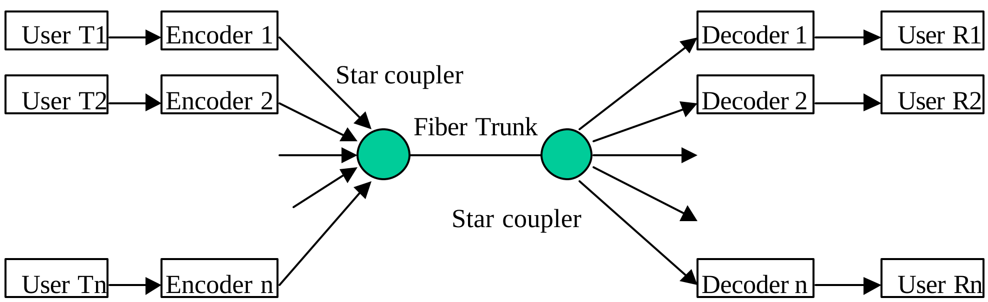

Fig. 1: Optical CDMA local area network

One of the great challenges in designing O-CDMA systems is selecting a set of optical address codes that have low periodic cross-correlation. The most common codes used to achieve this goal are prime codes and optical orthogonal codes (OOCs).[12] However, these codes suffer from high cross-correlation peaks compared to conventional bipolar codes, such as Gold, Kasami, and Hadamard codes. The bipolar nature of the codes is essential to achieving low cross-correlations and low multiple access interference. It is also important to select optimum bipolar codes with good or tolerable correlation properties to achieve the best system performance. We use liquid crystal SLMs to encode the power spectrum of a broadband source into bipolar Walsh codes for data modulation. The coding principle is the same as that described by Young's group[9] representing a bipolar code with two unipolar codes as shown in Figure 2. A unipolar supercode J of length 2N is formed by concatenating a sequence code U and its complement, $U \oplus \overline{U}$. Each element of J is composed of

$$J(i) = \begin{cases} U(i), & 0 \le i \le N-1 \\ \overline{U}(i-N), & N \le i \le 2N-1. \end{cases} \qquad (1)$$

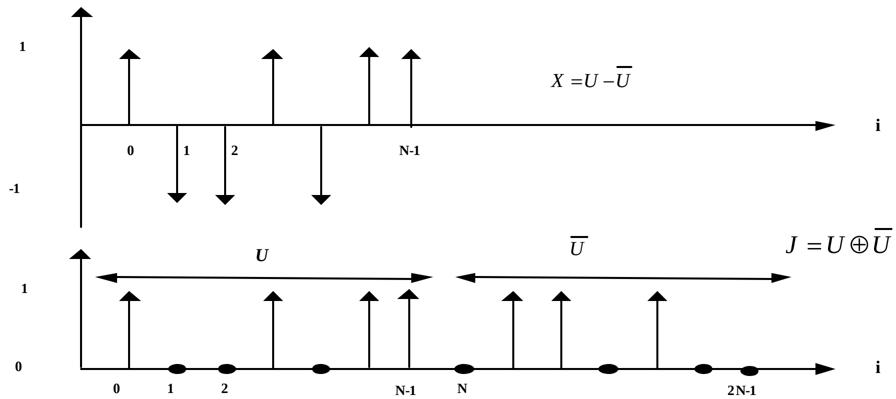

Fig. 2: Bipolar conversion of a uniploar code.

The key to system performance depends on constructing a decoder that implements a true bipolar correlation using only unipolar signals and intensity detection. This can be accomplished using two unipolar correlations, followed by a subtraction.[11] Let us consider two bipolar codes X and Y converted from their corresponding unipolar sequences U and V, and their unipolar supercodes $J = U \oplus \overline{U}$ and $K = V \oplus \overline{V}$. Since $X(i) = U(i) - \overline{U}(i)$ and $Y(i) = V(i) - \overline{V}(i)$, the zero-shift cross correlation of X and Y is

$$
\begin{aligned}
\Theta_{XY} &= \sum_{i=0}^{N-1} X(i)Y(i) = \sum_{i=0}^{N-1}\left[U(i) - \overline{U}(i)\right]\left[V(i) - \overline{V}(i)\right] \\
&= \sum_{i=0}^{N-1}\left[U(i)V(i) + \overline{U}(i)\overline{V}(i)\right] - \sum_{i=0}^{N-1}\left[U(i)\overline{V}(i) + \overline{U}(i)V(i)\right]. \qquad (2) \\
&= \sum_{i=0}^{2N-1}\left[J(i)K(i)\right] - \sum_{i=0}^{2N-1}\left[J(i)\overline{K}(i)\right] = J \cdot K - J \cdot \overline{K}
\end{aligned}
$$

The operations $J \cdot K$ and $J \cdot \overline{K}$ are unipolar correlations and therefore can be performed optically, as described in the following encoder/decoder system.

3. EXPERIMENTAL

3.1 Liquid Crystal Modulators and Coding Patterns

Liquid crystal optical modulators offer several advantages including large modulation depth, inertialess switching, low power dissipation, potential for large aperture operation, and low cost. LC modulators can also provide a variety of optical transmittance (reflectance) characteristics. LC devices can achieve different types of modulation including bipolar, real-axis, phase-only, coupled phase-amplitude and broad band phase shifters. This versatility is an additional advantage in today's atmosphere of budget constraints where multipurpose modulators are sought as a cost effective means to implement different subsystems. The various optical transmittance (reflectance) characteristics of LC modulators depend on the modulator architecture and the LC material used, as does the response time. Response times can range from several ms to 1 µs.

BNS has already developed four reflective SLMs based on silicon backplanes and converted them into successful products,[13,14] including a 128x128 binary SLM, 256x256 binary SLM, 128x128 multi-level SLM, and most recently a 512x512 multi-level SLM, which is currently being re-designed to utilize newer foundry techniques to enable a smaller optical head and significantly improved light efficiency. All four were developed exclusively for use in the optical processing arena.

For the application of conceptual demonstration for a one-dimensional O-CDMA system, we used a transmissive nematic 1x256 linear array SLM. The SLM has a pitch width of 107 µm and a pixel width of 100 µm. Twisted nematic LC material was filled into the SLM, and gives greater than π phase shift at 1.3-µm wavelength for full amplitude modulation. Only part of the SLM array was used (either 32 pixels or 64 pixels, which correspond to the diffracted beam size of the light source designed). Each single or grouped (when 64 pixels are used, two pixels are grouped as one chip) chip is one bit, composing a 32-bit bipolar code made of a 16-bit unipolar code and its complex conjugate. Two identical 1x256 SLMs have been fabricated and tested. They all give a π phase shift for 1.3 µm light when driven at a holding voltage of about ±6V. The SLMs are driven by 2 separate electronic drivers controlled via a PC. A program using C++ has been produced to control the 2 drivers simultaneously through the PC, so that different patterns (corresponding to different optical codes) can be simultaneously chosen. The program can change parameters like code patterns, offset position, holding voltages etc. The control of offset position for coded patterns is necessary for accurate alignment of code patterns produced from two different SLMs.

Figure 3 shows a 90° twisted nematic (TN) LC structure inside a cell. In the 90° TN cell, the director of the back surface is twisted 90° with respect to the front surface when the TN LC is in the unenergized state. When a linearly polarized light traversed through the TN LC cell, the plane of polarization follows the twist of the LC directors if the Mauguin's condition is satisfied, i.e., $d \cdot \Delta n >> \lambda$. Under this circumstance, the output beam remains linearly polarized except that its polarization axis is rotated by 90°. Figure 3 also shows that the directors of the 90° TN cell are perpendicular to the surfaces of the windows when the external electric field is applied. In this case, the plane of polarization will remain in its original orientation. With the output polarizer crossed with the input polarizer, the light intensity can be switched on or off. The light signal can be encoded into various "cross" and "bar" patterns.

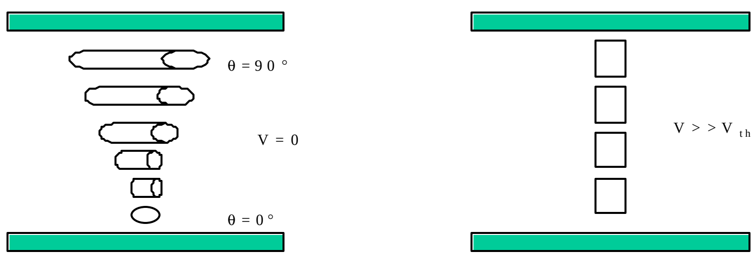

Fig. 3: Twisted nematic liquid crystal modulator.

3.2 Implementation of Signal Encoding

BNS has developed an optical system to encode a signal into spectral bipolar codes, as shown in Figure 4. The optical setup is similar to that used for the shaping of ultrashort optical pulses,[1] and it is composed of two gratings at the outer focal plane of a telescope. Single-mode optical fibers with appropriate collimators are used on all the ports. The 1.3-µm Super Luminescent Diode (SLD) fiber output beam is collimated via a GRIN lens (GL1) and diffracted by the grating (G1). The diffracted beam is collimated by a cylindrical lens (L1) of focal length 70 mm (with focal point at the grating). The collimated beam passes through the liquid crystal SLM that is between two crossed polarizers (P1 and P2). The pixelated liquid crystal elements are designed such that each wavelength channel can be driven independently. The coded channels are focused by the output lens (L2) and recombined by the output grating (G2) into a single beam that is coupled to output fiber via a GRIN lens (GL2). The other beam from the grating (G2) is used to monitor the encoding (spatial) structure through an IR viewer (ElectroPhysics-Model 7290A). The image is grabbed to the PC via a frame grabber. The image data is then analyzed and plotted with Mathcad software. By adjusting the polarization direction of P1 and P2, and the holding voltage of the SLM, which determines the LC phase delay, the encoding contrast can be optimized.

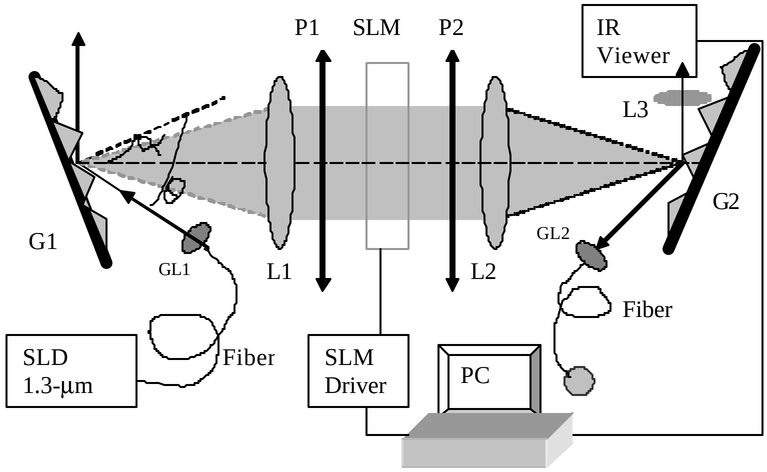

Fig. 4: Spectral encoding of the SLD beam via SLM modulation.

Figure 5 shows a typical light modulation result encoding the beam into a structure of 16 bright and 16 dark bars. This represents a 16-bit signal {1100 1100 1100 1100} and its conjugate. The left side is for the unmodulated beam, and the right side is the modulated (encoded) result. The surface plots are also shown below. The bright/dark bar structure can be clearly identified, and contrast is very good. The holding voltage of the SLM was set at ±6V for the results here, which corresponds to a π phase shift at 1.3-µm wavelength.

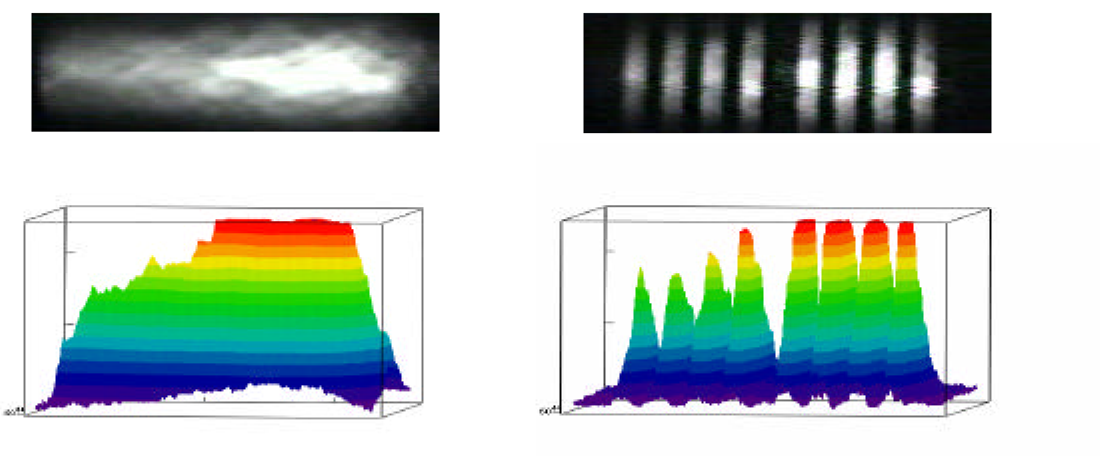

Fig. 5: Experimental plots showing the beam shapes with (right) and without (left) the SLM modulation (encoding).

3.3 Spectrum Decoding

To simplify a conceptual demonstration for the decoding principle, we set up the encoder/decoder system shown in Figure 6 to realize spectrum bipolar encoding and decoding. The left side of the system, composed of grating G1, lens L1 and SLM1 between two crossed polarizers P1 and P2, is for encoding. The power spectrum of the incoming light source is divided into 2x16 slices, or chips, and encoded into J pattern by programming the one-dimensional SLM1, as shown in Figure 5. This encoded pattern travels through free space and is "received" by the decoder on the right side. The encoded light passes SLM2 with a pattern corresponding to K, the code selected for detection. With the polarization of J code being 45° to the axis (vertical) of SLM2, the transmitted light of SLM2 consists of two orthogonal components being +45° and –45° from the SLM2 axis and producing signals proportional to $J \cdot K$ and $J \cdot \overline{K}$, respectively. The two light components are rotated by a polarization rotator (PR) 45° to the direction parallel or perpendicular to the optical axis (in vertical plane) of the polarization beam displacer (BD), so that they can be separated into two beams. These two beams are then focused by lens L2 and diffracted by the grating G2 into two collimated beams. For detection convenience, the two beams are further separated, 90° apart, by a polarization beam splitter (PBS), and collected onto two separate IR photo detectors, producing signals proportional to $J \cdot K$ and $J \cdot \overline{K}$, respectively. When a balanced detection method is used, the photodetector currents are subtracted from each other, and the resulting signal is proportional to the bipolar correlation Θ_{XY} of Eq. (2).

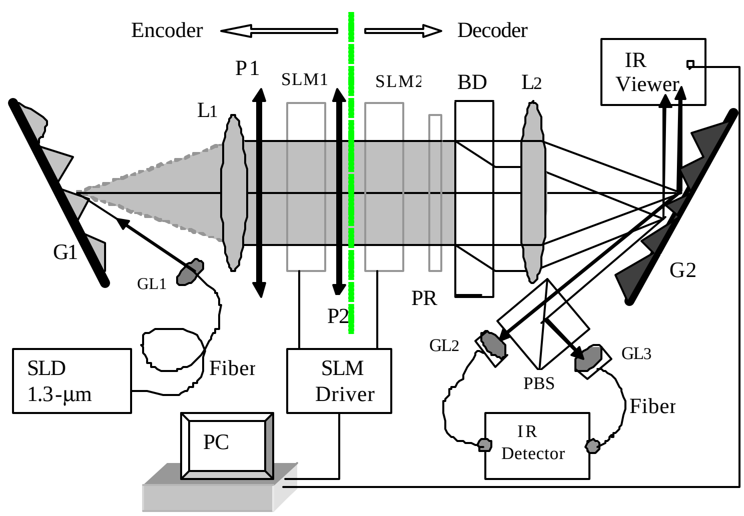

Fig. 6: Programmable spectral bipolar encoder/decoder, a setup for measuring correlations of the codes.
PR: Polarization Rotator; BD: Beam Displacer.

In a local area network, the received signal will be a superposition of spectra corresponding to the entire set of active user's codes. Since the receiver is linear in optical power, the output will be a superposition of their correlations with the desired code. A sequence of signals from the desired user will produce large value Θ_{XY} or $-\Theta_{XY}$. The interference between the desired user and other users is suppressed using bipolar codes to near zero, or very low magnitude as in Walsh or Gold codes. The high polarization selectivity of these bulk components coupled with the polarization rotation ability of liquid crystal elements makes switching possible with high extinction ratio and low crosstalk.

During the experiments, the two SLMs were first aligned with each other by looking at the coding patterns via the IR viewer. By setting the relative offset position of the two SLMs, they can be aligned conveniently. After the SLMs were aligned, the power difference of the two light components (i.e. correlation) was measured. Three orthogonal codes (and conjugates) are chosen: $J1$={1100110011001100 0011001100110011}, $J2$={1111000011110000 0000111100001111}, $J3$={1001100110011001 0110011001100110} and their complex conjugates $\overline{J}_1$, $\overline{J}_2$, $\overline{J}_3$. The decoder SLM2 was fixed to receive a particular coding pattern, say $J1$, while the code patterns of encoder SLM1 were varied sequentially to transmit any of the code patterns $J1$, $J2$, $J3$, $\overline{J}_1$, $\overline{J}_2$ and $\overline{J}_3$. Similar measurements were repeated by fixing SLM2 code pattern to each of the other codes. Figure 7 shows the correlations between the codes that were measured for the decoder SLM2 set to $J1$ (solid blocks) or $J3$ (hollow blocks) with the above single-user configuration. It can be seen that when the matched codes $J1$ and $\overline{J}_1$ are sent through SLM1, the decoder set to $J1$ responds with a large positive or negative correlation signal. Other codes had very small decoding outputs. While for the decoder set to $J3$, a large positive or negative correlation signal is obtained when the matched codes $J3$ and $\overline{J}_3$ are sent. The quantitative results for all the 3 sets of decoding settings are listed in Table 1, where all the values for each setting of the decoder SLM2 have been normalized to the autocorrelation value. It can be seen that in all cases, the cross correlation values are less than 14% of the autocorrelations. Good contrast between the autocorrelation and cross correlation values shows that a binary information symbol can be recovered by an appropriate threshold operation, demonstrating the feasibility of encoding and decoding for this optical array CDMA system.

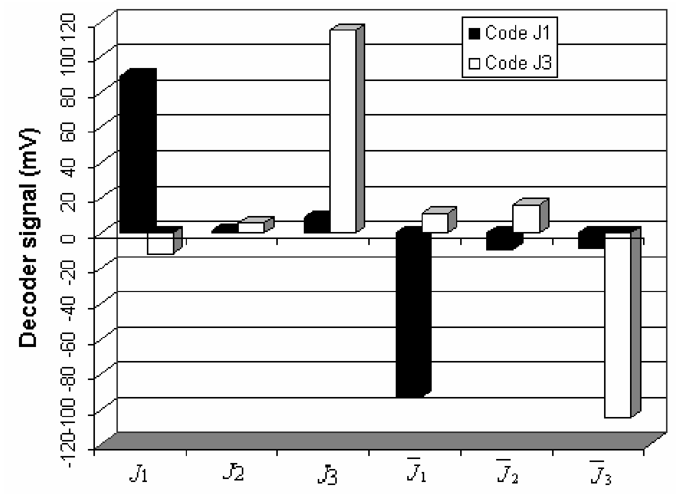

Fig. 7: Measured correlation values of the codes. The decoder SLM2 pattern was fixed as J1 or J3, while the encoder SLM1 sent all the patterns sequentially (J1, J2, J3, and complex conjugates).

Table 1. Auto and cross correlation measurements

		Signal Transmitted					
		J_1	J_2	J_3	$\bar{J}_1$	$\bar{J}_2$	$\bar{J}_3$
Decoder Code	$J1$	0.95	0.01	0.09	-1	-0.10	-0.09
	$J2$	-0.14	0.94	0.05	-0.13	-1	-0.13
	$J3$	-0.10	0.05	1	0.10	0.14	-0.91

4. CONCLUSION

We have carried out bipolar code design for the incoherent spectral Optical CDMA system, and realized a modulation and detection method that allows all-optical implementation of the bipolar codes. Using liquid crystal spatial light modulators, we performed a proof-of-principle demonstration of a reconfigurable one-dimensional encoder-decoder system. A broadband Super Luminescent Diode source has been spectrally encoded and decoded. The autocorrelation and cross correlation were measured, and good contrast between the autocorrelation and cross correlation values shows that a binary information symbol can be recovered by an appropriate threshold operation.

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