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Surface-micromachined free-space fibre-optic switches

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Indexing terms: Micromachining, Optical switches

A novel 2 × 2 free-space fibre-optic switch has been fabricated using surface-micromachining technology. The switch is monolithically patterned on the Si substrate. With this approach, the switch can be made compact, light weight and low cost. In addition, it is potentially integrable with other micro-optical elements and interface electronics. The switch is attractive for fibre-optic local area network applications.

Acquiring and distributing information is one of the most important processes conducted today and networks play an very important role in this process. Local area networks with fibre optics have received a great deal of interest because of their unique properties such as high bandwidth, immunity from current surges, no radio-frequency or electromagnetic interference, and more flexible requirements for their operating environment. For example, fibre-optic networks such as the fibre distributed data interface (FDDI), are widely accepted and supported in the industry for high speed local area networks.

Optomechanical switches are desirable for reconfiguring the fibre-optic networks because of the very low insertion loss and high isolation requirements. Most conventional fibre-optic switches are made in-waveguide, which results in high coupling losses. A free-space approach allows a low coupling loss and small cross talk. Currently, most optomechanical fibre switches are realised by manually assembled bulk optical elements and are expensive. Bulk micromachining of the Si substrate has been applied to free-space optical fibre switches [1]. In this approach, the hybrid-mounting of bulk optical elements and the wafer bonding technique are used. Therefore, monolithic integration is difficult and a substantial assembly is required. However, surface-micromachined micro-optical elements can be optically pre-aligned in the design stage and are monolithically patterned during the microfabrication process. They can be made compact and light weight, and are potentially integrable with optical sources/detectors and controlling electronics devices. The fabrication and characterisation of various three-dimensional micro-optical elements have been demonstrated [2, 3]. We report a novel free-space fibre-optic switch implemented using surface-micromachining technology.

Fig. 1 shows a schematic diagram of the switch. The switch consists of a three-dimensional movable mirror and four fibre-optic guiding rails. The mirror sitting vertically on a sliding plate is positioned at the centre of the switch and allowed to move along the x-axis. The mirror is coated with a 500nm thick gold layer to increase the reflectivity. Fig. 2 shows a scanning electron micrograph (SEM) of the mirror with the sliding plate. Four multimode fibres come from four diagonal directions along the guiding rails to the centre of the switch and form a cross shape. The facets of two fibres along the same diagonal direction are separated by <125mm. The switch has two operating states: CROSS and BAR. When the mirror/sliding-plate is moved away from the fibres (the centre), the fibres along the same diagonal directions are allowed to communicate with each other. This is defined as the CROSS state. In the BAR state, the mirror/sliding-plate is slid into the centre and the light signal is redirected into the orthogonal fibre. The top-view photographs of the switch with four multimode fibres in the CROSS and BAR states are shown in Fig. 3*a* and *b*, respectively. Fabrication of the switch is performed using the

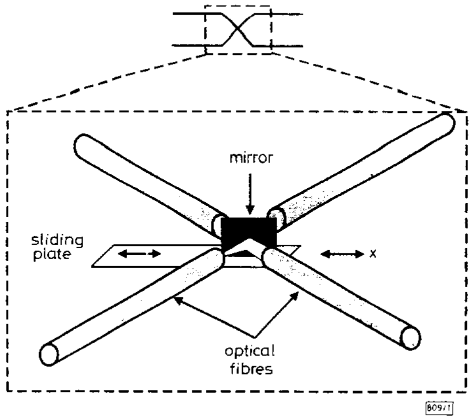

Fig. 1 *Schematic diagram of surface-micromachined free-space fibre-optic switch*

three-layer polysilicon surface-micromachining technology at MEMS Technology Application Center at North Carolina (MCNC) under the ARPA supported Multi-User MEMS Processes (MUMPs) programme. The fabrication process is similar to that of micro-Fresnel lenses [4] and microgratings [5].

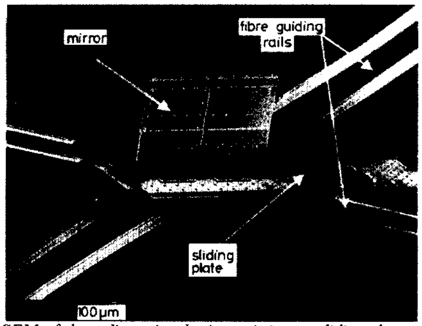

Fig. 2 *SEM of three-dimensional mirror sitting on sliding plate*

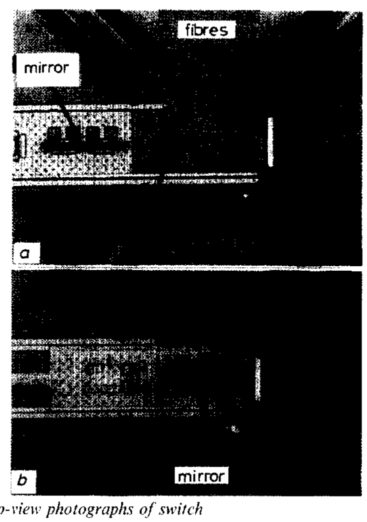

Fig. 3 *Top-view photographs of switch*

a In CROSS state
b In BAR state

Low insertion loss and cross-talk are important criteria for fibre-optic switches. The insertion loss, which includes fibre coupling loss and diffraction loss, can be reduced by employing collimating and focusing lenses as in [1]. However, bulk optical elements are difficult to integrate monolithically. Micromachined integrable lenses [2] can be used by optimising their efficiency. For optical switches with multimode fibres, the insertion loss can be lowered by reducing the fibre-to-fibre spacing. It has been shown theoretically that the coupling loss between multimode fibres could be as low as 1dB for a fibre-to-fibre spacing of 125mm, and 0.45dB for a fibre-to-fibre spacing of 50mm [6]. The insertion loss of the switch for both operating states has been measured with an LED source operating at a 1.3μm wavelength. The total insertion loss of the switch has been measured to be 2.8dB for the CROSS state and 3.1dB for the BAR state. From these two measurements, the reflectivity of the mirror is estimated to be 93%. The crosstalk between the two states is measured to be 26.1dB. The insertion loss and crosstalk can be further improved with a smoother gold coating on the mirror, an antireflection coating on the fibre facets, a smaller spacing between the fibres, and lensed fibre tips.

In summary, a free-space fibre-optic switch has been demonstrated using surface-micromachining technology for the first time. With its monolithic microfabrication capability and three-dimensional characteristics, the switch can be made compact, light weight and low cost. Surface-micromachined switches are potentially integrable with other micro-optical elements and controlling electronics, as well as microactuators, and are attractive in low cost high performance fibre-optic networks.

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Two-dimensional spatial codes for image transmission in multicore-fibre CDMA networks

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Indexing terms: Code division multiple access, Optical communication, Image coding

Spatial optical orthogonal signature pattern codes (OOSPCs) which are collections of (0,1) two-dimensional patterns with good correlation properties, are constructed. Such codes find applications, for example, to parallelly transmit and access images in multicore-fibre code-division multiple-access (CDMA) networks.

Introduction: Recently, two-dimensional (2-D) codewords (or matrices) which consist of $m \times n$ 2-D signature patterns of zeros and ones with weight (i.e. the number of ones) w were proposed for encoding binary image pixels in optical code-division multiple-access (CDMA) networks with multicore fibres [1]. The new technology enables parallel transmission and simultaneous access of 2-D images in multiple-access environments and these signature patterns are defined as an optical orthogonal signature pattern code (OOSPC).

The chosen OOSPC in [1] was based on the unnecessary restriction that every 2-D pattern has exactly one pulse per column, to ensure a good autocorrelation property. For multiple-access purposes, the autocorrelation property is useful only for timing extraction and synchronisation [2]. The restriction may not be necessary if both timing extraction and synchronisation can be obtained using other means such as, for example, pretransmission scheduling or channel-setup protocols.

In this Letter, the restriction is relaxed for such CDMA applications and three algebraic techniques for constructing these OOSPCs are reported. New cardinality bounds are provided to show that the new codes are optimal and support more codewords than those with the restriction. Furthermore, the new codes satisfy the restriction of at most one dot per column, and hence can be used in applications requiring, for example, frequency-hopping patterns.

Properties of OOSPCs: By definition [1], an $(mn, w, \lambda_a, \lambda_c)$ optical orthogonal signature pattern code $\mathbf{C}$ is a collection of binary (0,1) $m \times n$ matrices with Hamming weight w such that the following properties hold:

(i) *Autocorrelation:* For any 2-D pattern (or so-called codeword) $\mathbf{x} \in \mathbf{C}$ and two integers δ and τ such that $0 \le \delta < m$, $0 \le \tau < n$, and $(\delta,\tau) \ne (0,0)$, the 2-D binary autocorrelation sidelobe of $\mathbf{x}$ is no greater than an integer λ_a. That is

$$\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} x_{i,j}x_{i\oplus\delta,j\hat{\oplus}\tau} \le \lambda_a$$

where $x_{i,j} \in \{0, 1\}$ is an element of $\mathbf{x}$ at the ith row and jth column and $\oplus$ and $\hat{\oplus}$ denote modulo-m and modulo-n additions, respectively;

(ii) *Cross-correlation:* For any two distinct 2-D patterns (or codewords) $\mathbf{x}$ and $\mathbf{y} \in \mathbf{C}$ and two integers δ and τ such that $0 \le \delta < m$ and $0 \le \tau < n$, the 2-D binary cross-correlation of $\mathbf{x}$ and $\mathbf{y}$ is no greater than an integer λ_c. That is

$$\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} x_{i,j}y_{i\oplus\delta,j\hat{\oplus}\tau} \le \lambda_c$$

where $y_{i,j} \in \{0,1\}$ is an element of y at the ith row and jth column.

New bounds for OOSPCs: To show whether the constructed OOSPCs are optimal, two upper bounds for the cardinality of the codes with different autocorrelation constraints are derived, with some modifications, from Theorems 1 and 2 of [2]. Here, the cardinality of an OOSPC with $m \times n$ 2-D patterns of weight w is defined as $\Phi\ (mn, w, \lambda_a, \lambda_c) \triangleq \max\{|\mathbf{C}|:\mathbf{C}$ is an $(mn, w, \lambda_a, \lambda_c)$ OOSPC$\}$. For the special case of $\lambda_a = \lambda_c = \lambda$, the upper bound is given by

$$\Phi(mn,w,\lambda,\lambda) \le \frac{(mn-1)(mn-2)\cdots(mn-\lambda)}{w(w-1)\cdots(w-\lambda)} \quad (1)$$

Furthermore, by relaxing the autocorrelation constraint $\lambda + s$ for a positive integer s, the upper bound becomes

$$\Phi(mn,w,\lambda+s,\lambda) \le \frac{(mn-1)(mn-2)\cdots(mn-\lambda)(\lambda+s)}{w(w-1)(w-2)\cdots(w-\lambda)} \quad (2)$$

Owing to space limitations, the proofs of the bounds are reported elsewhere. Nevertheless, it is interesting to note that eqns. 1 and 2 are the same as the upper-bound equations for optical orthogonal codes (OOCs) in Theorems 1 and 2 of [2], and that both equations provide tight bounds for the 2-D OOSPCs and 1-D OOCs.