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7 × 7 DMD-based diffractive fiber switch at 1550 nm

A. Miles [a,*], B. Lynn [a], P.-A. Blanche [a], J. Wissinger [a], D. Carothers [b], L. LaComb Jr.[a], R.A. Norwood [a], N. Peyghambarian [a]

[a] College of Optical Sciences, The University of Arizona, Tucson, AZ 85721, USA
[b] Texas Instruments, 12500T I Blvd, Dallas, TX 75243, USA

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ABSTRACT

We have implemented and tested a free-space diffraction-based non-blocking 7 × 7 switch built primarily using off-the-shelf components and a commercially available digital micro-mirror device (DMD). This DMD is capable of switching 100 times faster than currently available technologies. The switch is protocol and bit-rate agnostic, robust against random mirror failure, and provides the basic building block for a fully reconfigurable optical add drop multiplexer (ROADM). Our design offers the potential to address the growing need for high speed scalable circuit switching for data centers and optical networks.

1. Introduction

The demands that bandwidth-intensive communication, entertainment, and storage are placing on existing data centers and optical networks are increasing exponentially. This growth continues to accelerate, with Cisco predicting annual global data center IP traffic to reach 7.7 zettabytes by the end of 2017 [1].

To minimize bottlenecks in information flow or data routing, the networks that handle this traffic rely on algorithms to continuously provision and allocate available bandwidth to where it is most needed. Further optimization of traffic is often limited by switching speeds and “loss of light time” caused by channel reallocation. The reconfiguration speeds of commercially available optical switches with large port counts are not yet sufficient for cross-connect and routing operations [2]. A smaller reconfiguration time leads to less time spent non-transmitting, making it a primary requirement of emerging switch technologies. Increasingly utilized hybrid architectures for modular datacenters, in which both electrical and optical switching technologies are used together, specifically highlight the need for fast optical domain switches [3].

Commercial 3D micro-electro-mechanical systems (MEMS) optical switches achieve switching by analog gimbaled movement of micromirrors to steer beams between outputs. One commercially available switch, based upon a 3D MEMS configuration, attains 25 ms switching time with an insertion loss of 2.0 dB across 320 × 320 ports [4]. This switching time is constrained by the analog nature of the switching, which relies on a feedback loop to settle the mirror at the position of best coupling. While this approach yields a very low insertion loss, this configuration is susceptible to port loss due to mirror or electronic damage that renders a given mirror inoperable.

An alternative approach is to use a liquid crystal on silicon (LCoS) spatial light modulator (SLM) as a dynamic diffractive element. The LCoS can modulate the refractive index across its aperture, providing a phase hologram for guiding. One implementation of this idea produced a 1 × 14 switch with insertion losses as low as 9 dB with switching times in the tenths of milliseconds [5]. A multi-mode ribbon fiber design recently described uses a custom molecule-based phase LCoS SLM, with 6 × 6 ports and 1 μs switching time, with a loss of 20.5 dB, and large polarization sensitivity. A large portion of this loss, 11.5 dB, cannot be reduced as it originates in the polarizer/SLM design [6].

Optical domain circuit switches such as those mentioned provide distinct benefits over hybrid switches that operate across both electrical and optical domains. These switches are protocol and bit-rate agnostic and free-space diffractive switches, such as the one we have implemented, are scalable to larger numbers of ports and amenable to modular implementations without the same linear increase in power consumption. These properties drove our choice of core technology when designing the switch.

* Corresponding author. Tel.: +1 5204503495; fax: +1 5206266219.
E-mail addresses: Amiles@optics.arizona.edu, alexanderashtonmiles@gmail.com (A. Miles).

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A digital micromirror device (DMD) provides an array of micromirrors capable of being switched between two angular orientations. A DMD based solution could fulfill requirements for speed, loss, and port count with fewer custom-made parts than competing designs. In addition, a holographic element-based switch can tolerate many mirror failures before dropping a channel, for example yielding losses of only 0.25 dB with failure of 2.5% of all micromirrors [7]. This resilience translates into a long device service life and architecture-independent operation, further distinguishing it from existing technology.

In our previous publication [7], we illustrated the feasibility of using these bulk manufactured components for free space beam steering, and demonstrated a visible light proof-of-concept device without fiber coupling. In this work, we have designed and implemented an innovative single mode fiber-coupled 7×7 port optical switch using a DMD as a holographic element. In addition we have further explored the system losses and possible mitigation strategies. The switch was characterized in terms of insertion loss, cross-talk, and polarization dependent loss, and was successfully tested in a network simulator.

2. Design

2.1. Concept

The design of this switch is based upon our previous proof-of-concept modeling and visible-light implementation [7]. The new system performs at telecom wavelengths in the C-band (1530 nm to 1565 nm) with coupling into and out of the system performed via single mode fiber. The switch utilized 7 single mode fiber inputs that can be independently switched to any or several of 7 single mode fiber outputs.

As shown in Fig. 1, each input fiber has a 4 mm diameter collimation lens, L1. The collimated light from each fiber is incident upon a unique sub-region of the DMD surface, shown in black in Fig. 2. Each of these regions display pre-calculated holographic patterns that diffract the light toward any given set of output fibers in the 1 cm^2 addressable area. A two inch diameter anti-reflection coated lens, L2, maps the angular components of the diffracted beam into the focal plane where they are coupled into the output fibers. An example of an image sent to the DMD to guide Input 4 to Output 4 as well as the labeling scheme for the couplers are shown in Fig. 2.

2.2. DMD

DMDs have been used in consumer projectors and rear-projection televisions for years, and as such there is an extensive body of data supporting their reliability and stability. Reliability studies have shown lifetimes of 10^{12} mirror cycles [8].

The DMD used in this implementation was a Texas Instruments DLP7000 with an array of 1024×768 micromirrors exhibiting a fill factor of 92%. The pixels are 13.68 μm square and correspond to a maximum diffraction angle of 3.25° by Bragg's law. By switching each mirror between two states, physically corresponding to tilting at $+12^\circ$ and -12° relative to the plane of the DMD, we were able to realize the binary amplitude holograms necessary for switching. As previously measured, the DMD has a loss of light time of less than 12 μs [9] and a total full-surface reconfiguration time including programming overhead and mirror settling of 43.5 μs [10], which as the sole active element determines the attainable switching speed. The size of the switching regions was dictated by the required grating resolution for effective fiber coupling, resulting in our choice of 7 inputs.

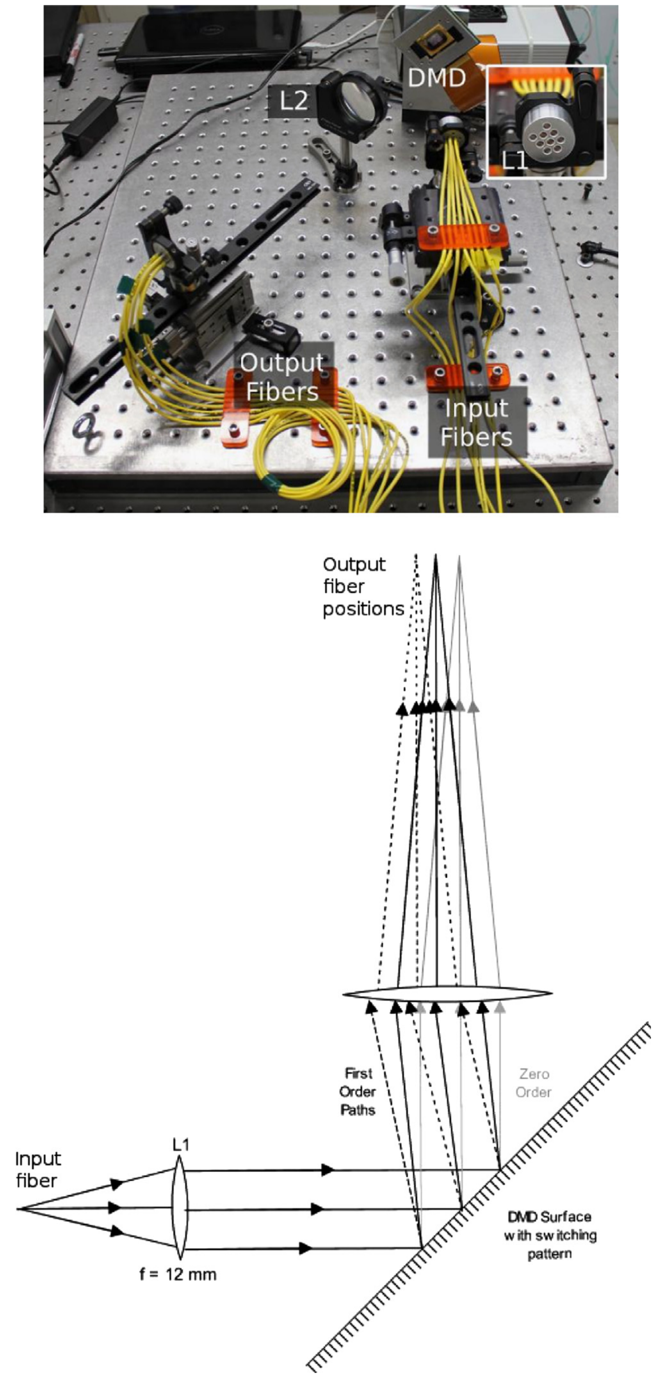

Fig. 1. (Top) a photograph of the switch with the input bundle on the right. The inset shows the front face of the input bundle with the collimation lenses. (Bottom) an optical schematic illustrating the switching of a single channel. The guided beams are shown with solid black and dashed black lines. Angles have been exaggerated for clarity.

2.3. Hologram design

The diffracted patterns resulting from transmission or reflection from a known structure have been calculated using scalar diffraction theory. The required holograms for ideal switching (i.e., one or more two-dimensional Dirac delta functions containing nonzero amplitude at all frequencies) contain an infinite number of frequencies, each with specific amplitude and phase [11]. However, the DMD can only produce two amplitudes, a single phase, and a finite set of frequencies, meaning that the phase information must be discarded, the amplitude information