Optical Switching and Networking 22 (2016) 42–53

Contents lists available at ScienceDirect

Optical Switching and Networking

journal homepage: www.elsevier.com/locate/osn

Advanced three-dimensional MEMS photonic cross-connect switch for nonblocking all-optical networks

I. Plander [a], M. Stepanovsky [b,*]

[a] European Polytechnic Institute, Osvobozeni 699, 686 04 Kunovice, Czech Republic
[b] Czech Technical University in Prague, Zikova 1903/4, 166 36 Praha 6, Czech Republic

ARTICLE INFO

Article history:
Received 23 September 2014
Received in revised form
9 March 2016
Accepted 25 April 2016
Available online 28 April 2016

Keywords:
Double-gimbaled MEMS-based micromirror cross-connect
Switching time
Optimization
Multiphysics model
Simulation
Open-loop and closed-loop control

ABSTRACT

The 3D MEMS optical switch utilizes highly reflective micromirrors to manipulate an optical signal inside the switch directly without any conversions, offering bit rate and data protocol independency. As indicated by the simulation results of this paper, many of developed micromirrors (by various companies) are not optimized well in the sense of dynamic behavior and can be further improved. This non-optimal design negatively limits the switching speed of the optical switch. The switching mechanism is in a fact the two-way coupling between the mechanical structure (micromirror) and electrostatic field (electrodes) – see e.g. Ananthasuresh [1, Sec. 11.4]. This introduces additional effects resulting in coupled rotation of the micromirror about its axes – the cross-axis coupling effect. Existing solutions are mainly focused on the optimization of the control strategy of the micromirror aiming to suppress its oscillations and to minimize the switching time. Our approach is foremost focused on the optimization of dynamic characteristics of the micromirror. This suppress negative effects of cross-axis coupling and thus allows further reduction of the switching time of the switch. Our results are supported by simulation experiments, which consider the switching element as multiphysics system described by partial differential equations.

1. Introduction

All-optical (OOO) switching has emerged as the alternative to electronic (OEO) switching with the realization of OOO networks [2,3]. Recently, energy efficiency has become a discussed topic. Hybrid solutions combining slow and low power-consuming switches (circuit switching, long burst switching) and fast switches (short burst switching, packet switching) are considered [4,5]. Today's 3D MEMS (three-dimensional microelectromechanical systems) photonic switches [6–8], are able to build a fully-automated, dynamically reconfigurable, highly-scalable physical layer (from 10 Gbps to 40 or 100 Gbps and beyond without additional investment) and to provide a required growing network bandwidth and agility for various service providers, datacenters, cloud computing networks, etc. 3D MEMS switches are also in line with an energy-efficient design of core networks [4,9]. The optimal configuration for 3D MEMS switches (mutual position of micromirror arrays, their distance, etc.) was studied in the past and several solutions were proposed [10–14]. Similarly, the static and dynamic characteristics of individual micromirrors were analysed [15–21]. Nevertheless, the three degrees of freedom, in which both two degrees of freedom in micromirror tilting and one degree of freedom in bending are considered, is rarely discussed. The understanding of the complex dynamic behavior of the micromirror is very important for its design and for its motion control.

The first goal of this paper is to present a multiphysics model which can be used for the analysis and optimization of 3D MEMS-based double-gimbaled torsion micromirrors. The second goal is to open the question of optimal design of torsion micromirrors in terms of dynamic behavior and to discuss existing micromirrors. In the past, the mechanical structure (i.e., the micromirror shape and micromirror suspension) was not optimized enough, and thus, the used control strategy needed to take into account non-optimal micromirror design, which is characterized by unsuitable dynamic characteristics. The optimization of the micromirror structure is a very important step in its design regardless of the control strategy used. In this paper we present the multiphysics model of the 3D MEMS cross-connect. The model is represented by the system of partial differential equations. These equations are discretized by Finite Element Method (FEM), implemented by the authors as simulation tool in Matlab, and consequently simulation experiments were performed. Moreover, we propose simple optimization strategy, which helps to avoid difficulties with cross-axis coupling effect

* Corresponding author.
E-mail addresses: ivan.plander@tnuni.sk (I. Plander), michal.stepanovsky@fit.cvut.cz (M. Stepanovsky).

http://dx.doi.org/10.1016/j.osn.2016.04.007
1573-4277/

and we also present case studies illustrating differences during micromirror switching between optimized and non-optimal micromirror design.

This paper is organized as follows: Section 2 briefly describes the principle of switching inside the 3D MEMS optical switch; Section 3 presents a multiphysics model of the cross-connect, a model used for cross-connect analysis and optimization; Section 4 gives insight into control of the cross-connect, where both open-loop and closed-loop control are described; Section 5 presents simulation case studies, which compare open-loop versus closed-loop control and non-optimized versus optimized design; Section 6 explains the rationale behind optimization strategy; Section 7 discusses simulation results and compares them with existing cross-connects; finally, Section 8 presents our conclusions.

2. Principle of 3D MEMS switch

3D MEMS-based switches use micromirrors of diameter of the order of some hundreds of micrometers for optical beam switching between input and output ports. Each micromirror can rotate about two orthogonal axes and its actuation is typically carried out by electrostatics, where electrodes underneath the micromirror form a capacitor with the micromirror itself (see Fig. 1).

The 3D architecture typically employs two arrays of micromirrors, each aligned to an array of collimated input or output fibers. This requires the use of $2N$ mirrors for N ports, considerably less than 2D architecture. Fig. 2 shows an example of an implementation of a 3D optical MEMS switch. The switch consists of an input fiber array, an input lens array, two parallel MEMS mirror arrays in 3D space, an output lens array, and an output fiber array. Each input fiber directs light to a mirror on the input array while the input mirror steers the optical beam to any output mirror, which, in turn, steers the light to an output fiber. Due to the symmetrical design, both input and output mirrors require the same deflection capacity. Uniform lens arrays with optimized focal length are used to collimate the beams in and out of the arrays of fibers.

The Fourier transform lens placed between the micromirror arrays (Fig. 2 – left) allows for several advantages: lower maximum angle requirement, smaller micromirror size, greater tolerance to micromirror curvature, and lower switch crosstalk [22,23]. Other configurations and improvements of the switch structure are also possible. The configuration from Fig. 3 (left) their optical switch [24]. The toroidal concave central mirror as the optical Fourier transform element can be utilized also [14] (see folded structure in Fig. 3 – right). This concave mirror also enables a compact layout of the switch. Nevertheless, all these configurations have one thing in common: they require micromirrors with the ability to rotate about two independent axes – see Fig. 1 (left).

As the optical beams are spatially and temporally switched, they do not interact when crossed; hence blocking does not occur in 3D space switches.

The optical power loss in optical MEMS switches is determined by the following factors: Gaussian beam divergence, air absorption, mirror angular misalignment, mirror reflection loss, mirror curvature and coupling loss between fibers and the switch [25]. The values of the first three factors increase with the optical path length. Fig. 4 illustrates the optical beam from the input fiber to the output fiber. For a certain input fiber, the distance between the transmitting plane and input mirror is fixed, and the total optical path length depends on required output fiber. The optical beam in free-space is a Gaussian beam.

The electrical field of a Gaussian beam is a function of its axial coordinate z and its radial coordinate r, given by [26]:

$$E(r,z) = \underbrace{E_0 \frac{\omega_0}{\omega(z)} \exp\left(\frac{-r^2}{\omega(z)^2}\right)}_{\text{amplitude factor}} \cdot \underbrace{\exp\left(-j\left[kz - \tan^{-1}\left(\frac{z}{z_0}\right)\right]\right)}_{\text{longitudinal factor}} \cdot \underbrace{\exp\left(\frac{-jkr^2}{2R(z)}\right)}_{\text{phase factor}} \quad (1)$$

where z is the propagation distance, $\omega(z)$ is $1/e$ beam radius versus z, and $R(z)$ is the curvature of the wave-front versus z. Describing the Gaussian divergence during beam propagation, $\omega(z)$ and $R(z)$ are given as follows:

$$\omega(z) = \omega_0 \sqrt{1 + (z/z_0)^2}, \quad (2)$$

$$R(z) = z[1 + (z/z_0)^2], \quad (3)$$

$$z = \pi\omega_0^2/\lambda, \quad (4)$$

where z_0, called Rayleigh range, is the length along the beam path where its radius is increased by a factor of $\sqrt{2}$. ω_0 is the minimum radius of the beam, called beam waist, which is determined by the lens before the input fiber, and λ is the wavelength of signal. Because the light beam is Gaussian divergent, the power reflected by a mirror of radius r at position z is as follows [26]:

$$P_0 = P_1\left(1 - \exp\left(\frac{-2R^2}{\omega^2(z)}\right)\right). \quad (5)$$

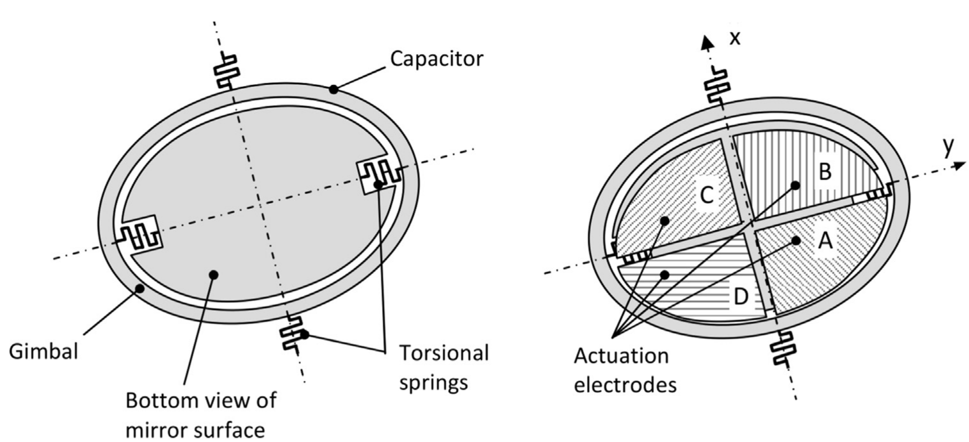

Fig. 1. Electrostatic actuation of the micromirror.