Nonvolatile bistable all-optical switch from mechanical buckling

Varat Intaraprasonk[1] and Shanhui Fan[2,a)]
[1]Department of Applied Physics, Stanford University, Stanford, California 94305, USA
[2]Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA

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We propose a nonvolatile all-optical bistable optomechanical switch comprising two parallel buckling waveguides. The bistability comes from mechanical buckling so the operation of the switch does not require maintenance power. The switching and reading of the states are all optical; they involve relatively strong and relatively weak optical pulses, respectively, similar to conventional bistable optical switches. © 2011 American Institute of Physics.
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Under a given input condition, a bistable optical switch is characterized by the existence of two operating points or states, both of which are stable against small fluctuations. Such a device is important for a number of optical information processing architectures. Examples of bistable optical switches include an optical cavity with Kerr nonlinearity[1–4] and bistable laser diodes.[5,6] In the former examples, the two bistable states have either low or high transmission coefficients. In order to write, i.e., switch between the two states, a relatively strong optical pulse is sent in. In order to read the state, a relatively weak pulse is sent in and the output can be used to determine the state. One problem with all previously considered bistable optical switches is that they are volatile; in order to maintain the stable states, continuous power input is needed.

In this letter we propose a nonvolatile bistable optomechanical switch which is all optical in writing and reading processes. In this switch, the buckling[7,8] of a pair of waveguides creates the two bistable states. To write, i.e., to switch between the two states, we propose to send in a relatively strong pulse and utilize the generated optical force. To read, we propose to send in a weak pulse since the transmission depends on the waveguides' mechanical configurations. Because the bistability is a mechanical one, this switch is nonvolatile; the states do not require continuous power to maintain.

Our switch comprises two adjacent suspended rectangular waveguides.[7,8] Each waveguide is connected to fixed input/output optical waveguides [Fig. 1(a)]. We utilize the bistability that arises from the two buckling configurations of the waveguides, which result in "near" state and "far" state [Fig. 1(b)]. For this design, each waveguide has length $L = 15\ \mu m$, thickness $t = 400$ nm, and width $w = 200$ nm, separation between the two waveguides $d_0 = 60$ nm [Fig. 1(c)]. The material is silicon with the biaxial modulus,[9,10] $E = E_0/(1-\nu) = 257$ GPa, where $E_0 = 185$ GPa is Young's modulus and $\nu = 0.28$ is Poisson ratio.

Each of the waveguide can be described mechanically as a buckling beam. When a beam is under mechanical stress σ ($\sigma < 0$ means compressive stress), buckling will occur if the compressive stress exceeds the critical stress σ_{cr}, i.e., $|\sigma| > |\sigma_{cr}|$. For our system, numerical simulation gives $\sigma_{cr} = -149.87$ MPa, as can be visualized by plotting the elastic energy U as a function of the displacement in x-direction of the midpoint of the beam A_m for different values of stress [Fig. 1(d)]. For $\sigma = -149.76$ MPa ($|\sigma| < |\sigma_{cr}|$), U has the minimum at $A_m = 0$, so the beam is unbuckled. For $\sigma = -150.14$ MPa ($|\sigma| > |\sigma_{cr}|$), U has an energy barrier between the two minima at $A_m = \pm 10$ nm $\equiv \pm A_{eq}$, so the beam buckles into either of the two bistable states. These results agree well with the analytical theory.[10]

For our design, we choose $\sigma = -150.14$ MPa. With this choice of the stress near σ_{cr}, the energy barrier between the two bistable states is low, allowing fast switching speed and low switching power. Also, at this σ, the barrier height of 0.2 aJ $= 50 k_b T$ (k_b is the Boltzmann constant and T is the temperature) is sufficiently large to maintain thermal stability, following the criterion in magnetic memory design.[11,12] In practice, fabrication imperfections may require energy barrier higher than this thermal limit; larger $|\sigma|$ then can be chosen at the cost of higher energy per switch and longer switching time. To achieve a truly nonvolatile switch, this stress has to be maintained by passive methods such as stress-engineering during fabrication.[7,13] However, if necessary, additional stress can be supplied by active methods

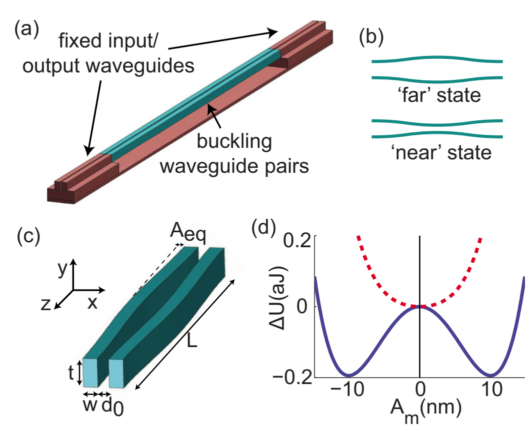

FIG. 1. (Color online) (a) The schematic for the switch. The middle part of the beams (in blue) are a buckling waveguide pair that is suspended. The two ends (in red) are fixed waveguides that also provide mechanical supports. All parts are silicon. (b) Top view of the waveguide pair in far and near states. (c) Dimensions of the waveguide pair. (d) Elastic energy as a function of midpoint x-displacement for an individual waveguide under longitudinal stress [$\Delta U = U - U(A_m = 0)$]. $\sigma = -149.87$ MPa (dashed) shows no buckling. $\sigma = -150.14$ MPa (solid) shows two buckling states at $A_{eq} = \pm 10$ nm.

a)Electronic mail: shanhui.fan@stanford.edu.

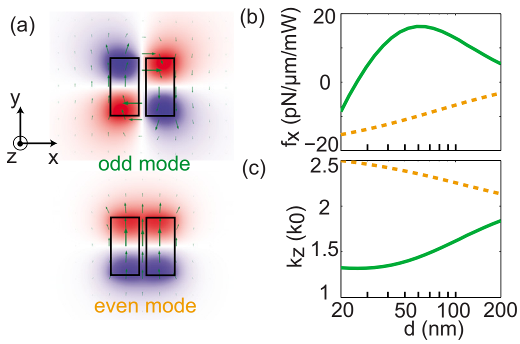

FIG. 2. (Color online) (a) The plots the cross section of two parallel straight pair of waveguides showing the two optical modes of interest. Shading denotes electric field E_z. Arrows denote E_x and E_y. Solid lines denote the beams' boundaries. (b) The x-component of the optical force per length, normalized by input power (f_x), and (c) propagation constant (k_z), as a function of separation d, for the odd mode (solid) and the even mode (dashed).

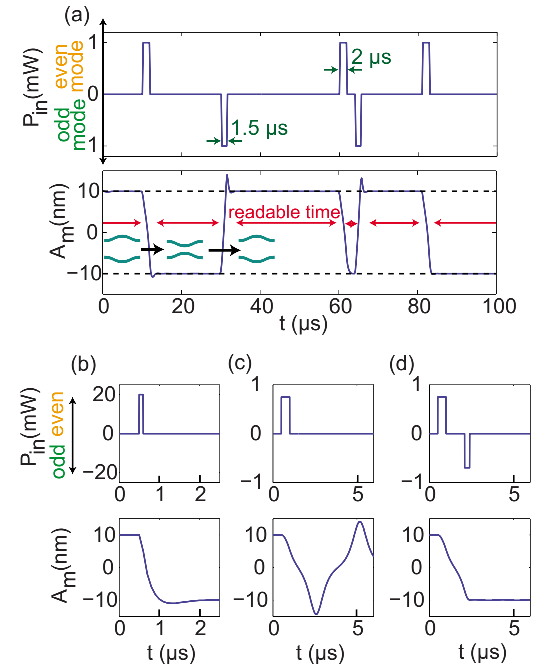

FIG. 3. (Color online) Switching scheme. In each pair of plots, the top plot is the power and the mode choices of the input optical pulse; the bottom plot is the x-displacement of the midpoint of one of the buckling beams (+10 nm and −10 nm indicates the pair is in far or near states, respectively). The damping is $\tilde{b}=2800$ N s m^{-3} for (a) and (b), $\tilde{b}=28$ N s m^{-3} for (c) and (d).

such as on-chip piezoelectricity[14,15] or resistive heating.[8]

To switch between the states, we send in a relatively strong optical pulse and utilize the resulting optical force.[16] The optical force between two parallel waveguides is bipolar, with the sign depending on the optical modes.[17,18] We first consider a pair of parallel straight waveguides. The optical pulses used have free-space wavelength $\lambda=1550$ nm. The permittivity of silicon is $\epsilon=12.38$. The strain dependence of ϵ is ignored because the uniform strain from the longitudinal compressive stress is much larger than any local additional strain from buckling, so any correction to ϵ would be uniform to the first order and does not change the optical properties significantly. The two optical modes of interest are the odd and the even modes shown in Fig. 2(a). The calculated optical force per length in x-direction, normalized by the total input optical power, is plotted in Fig. 2(b) (positive sign means repulsive force), as a function of the separation d between the two waveguides. The even mode gives attractive force for any d and is responsible for the switching from far to near state. The odd mode gives repulsive force for $d > 30$ nm and is responsible for switching from near to far state. Since both attractive and repulsive forces are needed, the separation d_0 between the waveguides in the absence of buckling is chosen to be $d_0=60$ nm. In our case, the buckling waveguides are not strictly straight but because the curving is very gradual (maximum deflection of 10 nm over 15 μm length), the value of optical force described above gives the local force per length $f_x(z)$ as a function of local separation $d(z)$.

We now simulate the switching dynamics using a two-dimensional time-dependent mechanical simulation. The input of the simulation is the time-dependent optical power in even or odd modes. This optical power, at a particular time step, is considered continuous wave across the whole waveguides because the mechanical motion is much slower than the optical frequency. In each time step of the simulation, the optical input and the current mechanical configuration give the local force distribution on each waveguide, which is used to move and update the mechanical configuration for the next time step.

In this time-dependent simulation, damping is needed so that the waveguide can settle down in one of the bistable points in finite time. We assume the damping force per area to be of the form $-\tilde{b}v$, where v is the velocity and $\tilde{b}$ is the damping constant. As a reference, the squeeze film air damping, due to the film of air between the two waveguides, for our geometry is approximately $\tilde{b}=1400$ N s m^{-3} at 1 atm pressure.[19]

The measured quantity from the simulation is the midpoint deflection $A_m(t)$ of one of the waveguide ($A_m=+A_{eq}=+10$ nm means the pair is in the far state). In Fig. 3(a), we plot the switching sequence, assuming a critically damped system with $\tilde{b}=2800$ N s m^{-3}. The even mode pulse is used to switch the system from the far state to the near state, and the odd mode pulse is used to switch the system from the near state to the far state. We see that the switching time is 3 μs, and the switching energy is 2 nJ for far to near state and 1.5 nJ for near to far state. For this system, the switching time can be lowered, while consuming the same switching energy, by increasing the peak power. As seen in Fig. 3(b) for the switching from far to near state, increasing the peak power to 20 mW, while keeping the switching energy of 2 nJ, reduces the switching time to 1 μs.

We now consider the same system with a much lower damping constant of $\tilde{b}=28$ N s m^{-3}, which can be achieved, for example, by lowering air pressure.[19] In the critically damped case as considered above, much of the energy required in switching is dissipated through the damping. Thus, our objective here is to reduce the required switching energy by lowering the damping. However, at such low damping, applying a single switching pulse makes the system oscillates between the two states for many cycles, with the final state being very sensitive to the system parameters [Fig. 3(c)]. To overcome this difficulty, we propose to use a second switch pulse that applies the force in the direction opposite to the first pulse. With the use of the second pulse, the

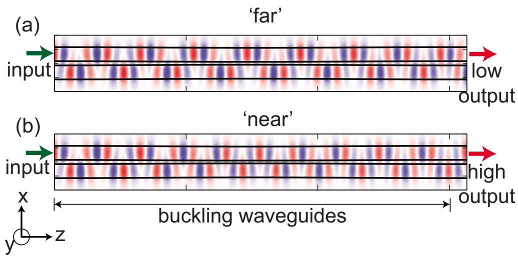

FIG. 4. (Color online) Reading scheme. The plots show the value of electric field E_z at the plane $y=t/4$ away from the center of the beams for the buckling states of (a) far state (low transmission state) and (b) near state (high transmission state). The boundary of the waveguides is shown in solid lines. The input is sent into the top waveguide from the left. The output is measured from the top waveguide at the right.

system can immediately settle down in the desired state due to the second switch pulse acting as a brake [Fig. 3(d)]. The total energy of the two switching pulses combined [590 pJ for Fig. 3(d)] is significantly lower compared with the critically damped case considered above.

To read the states, an optical wave is sent into one of the waveguides. The strength of the reading optical field can be chosen to be sufficiently weak such that the state of the switch is not perturbed. The output is then collected at an appropriate position from one of the output waveguides, and the difference in transmission can be used to determine the states. This is illustrated in Fig. 4. The input is sent into the top waveguide from the left. The output power is collected from the top waveguide on the right. The near state is then the high transmission state and the far state is the low transmission state. The transmission difference between the two states arises from the different propagation constants of the coupled waveguides in the two states, as shown in Fig. 2(c). Unlike the writing process, the reading does not involve mechanical motion; therefore, the reading speed can be much faster than the writing speed.

In summary, we design a nonvolatile bistable switch made from a pair of buckling waveguides. Because the bistability comes from mechanical buckling, no continuous power is needed to maintain the states. The writing and reading are all optical similar to standard optical switches. Here as a proof of principle we have simulated a relatively simple design. One could further reduce the required switching power with the use of optical resonators that enhances optical force.[20–23] Also, in our current design, the two waveguides are assumed to be identical, thus the eigenmodes of the coupled waveguides are either even or odd. For waveguides that are not identical, for example, due to fabrication inaccuracy, one could also launch the eigenmodes of the coupled waveguides in order to achieve the switching action.

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