Design of Mechanically Tunable Optical Filters with Microring Resonators

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***Abstract*—Design strategies for the mechanically tunable optical filters with microring resonators and comb-drive actuators are discussed. Electromechanical simulation results are combined with the electromagnetic analysis of the device. A method to design comb-drive actuators to achieve linear resonant wavelength-voltage characteristics is presented.**

Keywords—tunable optical filters; microring resonators; comb-drive actuators

I. INTRODUCTION

Tunable optical filters are essential building blocks in wavelength division multiplexing (WDM) optical fiber communication systems. Optical filters are often realized by microring resonators on a photonic integrated circuit (PIC) platform where their planar structures and compact sizes are quite beneficial. Fabricated microring resonators have been reported with very high quality factors—in case of silicon rings, up to a few hundreds of thousands [1, 2]. To tune the resonant wavelength of the filters, either thermo-optic effect with Joule-heating [3] or free carrier injection method [4] has been widely utilized. Both of the mechanisms rely on electric current for control, which cannot be removed in order to maintain the tuned resonant wavelength. Therefore, tunable optical filters based on these two methods demand continuous standing power consumption during most of their operations. Although such power consumption by a few devices may not pose a significant problem, for applications that require tens or hundreds of tunable filters, the power consumption issue can become fairly serious. Recently, an alternative tuning mechanism was proposed by several groups including the authors for microring-based tunable optical filters, namely index modulation by evanescent coupling [5-7]. In this method, a suspended waveguide which is also called an index modulator is brought close towards a microring resonator to induce evanescent coupling from the resonator to itself, causing change in effective indices of the modes propagating through the resonator. By varying the distance between the modulator and the resonator, the resonant wavelength of the filter can be tuned in a continuous fashion. For mechanical control of the index modulator, a voltage-controlled mechanism can be used, such as electrostatic and piezoelectric actuation in order to minimize the standing power consumption requirement. Power is needed only during a transition while the resonant wavelength is changed. Once the tuning is completed, no more current is required to maintain the tuned state. This paper presents the design strategy for this mechanically tunable optical filter, with the main focus on the actuator design.

II. OPERATION PRINCIPLE

Fig. 1 shows the schematic diagrams of the mechanically tunable optical add-drop filter device proposed by the authors

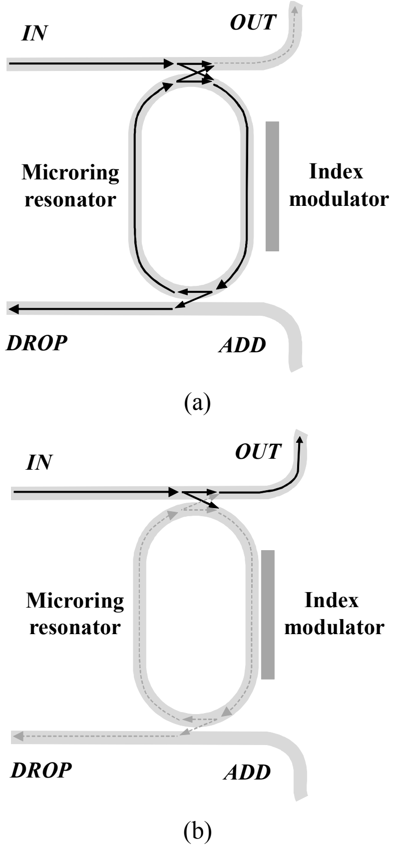

Fig. 1. Schematic diagrams (top views) of a mechanically tunable optical filter with a microring resonator and an index modulator (a) at resonance and (b) at off resonance. Dashed gray lines indicate very weak field intensity.

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[5], which is operated by an in-plane actuator. When the index modulator is separated from the resonator with a sufficient gap (fig. 1-a), light propagating inside the resonator is hardly affected by the presence of the index modulator, and at resonance, it is sent to the "*DROP*" port via coupling through the microring resonator. When the index modulator is brought closer to the resonator (fig. 1-b), effective indices are changed around the interaction region, and the original resonant wavelength is directed to the "*OUT*" port because it is no longer in the resonant condition. In this circumstance, the resonant condition is met at another wavelength, which means tuning of the resonant wavelength. Optical simulations (both analytical and numerical) were carried out for the proposed filter devices and the detailed results can be found in [5]. The simulations confirmed the operation principle of the proposed device. This study in the optical domain needs to be combined with the electromechanical analysis to fully comprehend the device operation characteristics. The aim of this paper is, therefore, to present the characteristics of the proposed device based on theoretical study by putting optical and electromechanical analyses together. At the same time, design of the electrostatic actuator is visited in detail to optimize the device performance, especially in terms of wavelength-voltage linearity.

III. DESIGN

Among various in-plane actuators available in microelectromechanical systems such as Lorentz-force actuators, hot-arm-cold-arm actuators, scratch drive actuators, and so on, electrostatic comb-drive actuators are most well-suited for the current device from the minimal standing power consumption point of view.

A. *Single Comb-Drive Actuator (No Biasing)*

Fig. 2(a) depicts a schematic diagram of one design for the optical filter with a comb-drive actuator, which is the most straightforward design and also appropriate for the required actuation range. For the device in consideration, of which geometries and material parameters are given in table I, in-plane translation of 300 nm is sufficient for the resonant wavelength tuning of one full free spectral range (11 nm) around the wavelength of 1560 nm [5]. There are two options in terms of the direction of actuation, i.e. pulling the index modulator towards the resonator (to the left) or pulling it away from the resonator (to the right). The former is preferred for a practical reason: in the latter, the index modulator has to be fabricated very close to the resonator, with a gap less than 15 nm. However, the former approach, i.e. pulling it towards the resonator, is not without a drawback: complexity in control of the resonant wavelength with voltage. As illustrated in fig. 2(a), the resonant wavelength is a highly nonlinear function of the gap between the index modulator and the resonator (in the figure, the resonant wavelength is plotted against the displacement of the index modulator). Displacement of a typical comb-drive actuator with rectangular and parallel teeth (fig. 2-a) is roughly proportional to the square of the voltage applied. Therefore, the relationship between the resonant wavelength and the applied voltage becomes even more nonlinear as given in figs. 2(a) and 3(a) because two nonlinear functions are combined with the same trends, i.e. while their second derivatives have the same signs. This almost "diode-like" profile given in fig. 3(a) demands complexity in control electronics since small variation in voltage will cause significant change in the filter characteristics at longer wavelength, which becomes an even more serious issue as the number of filter devices grows in one system.

TABLE I. GEOMETRICAL AND MATERIAL PARAMETERS OF THE DEVICE USED IN THE SIMULATION.

Description	Symbol	Value
Number of comb fingers	N_f	50
Spring constant	k_s	0.27 N/m
Comb finger thickness	T_f	200 nm
Comb finger maximum gap	d_0	400 nm
Refractive index of resonator		3.48
Refractive index of modulator		2.2
Resonator width		200 nm
Perimeter of resonator		62.8 μm
As-fabricated gap between modulator and resonator		300 nm
Modulator width		200 nm

B. *Dual Comb-Drive Actuators (Biasing)*

One way to address the issue of nonlinear characteristics is to reverse the convexity of one function, in this case, that of the comb-drive actuator. This can be achieved by adding second comb-drive actuator, and using the original one as a bias. When the control voltage V is applied to the second comb (right) and a bias voltage V_{bias} is applied to the original comb (left), the displacement x can be roughly expressed as,

$$x(V) = \frac{\varepsilon_0 N_f T_f}{k_s d_0}\left(V_{bias}^2 - V^2\right), \tag{1}$$

where ε_0 is the permittivity in vacuum (other variables are defined in table I and fig. 2-b). As depicted in fig. 2(b), now the displacement curve opens up downward. As a result, filter characteristics become more linear as shown in figs. 2(b) and 3(b). It should be noted that the bias voltage has to be equal to or greater than the voltage that can make a full sweep—i.e. free spectral range—obtainable in the resonant wavelength.

C. *Finger Shape Modification – Exponential Gap Variation*

Improvement in the linearity of the resonant wavelength with respect to the control voltage was further pursued with modification in the comb-drive finger designs [8]. Linear and quadratic variations of teeth gaps were studied first with minimal improvement. Then, exponential gap variation was examined as drawn in fig. 2(c), which was thought to work naturally in compensating the highly nonlinear relationship between the resonant wavelength and the modulator displacement. The simulation result is given in fig. 3(c). As expected, the linearity of the filter characteristics is further improved by utilizing exponential-gap-varying comb-drive actuators.

D. *Finger Shape Modification – Rigorous Calculation*

The resonant wavelength-voltage (λ_r-V) characteristics of the filter can become almost linear by rigorously calculating the comb finger shapes, i.e. by solving the following equation.

$$\frac{d\lambda_r}{dx} \bullet \frac{dx}{dV} = C_0 \,, \tag{2}$$

where C_0 is a constant, which is equal to the slope of the

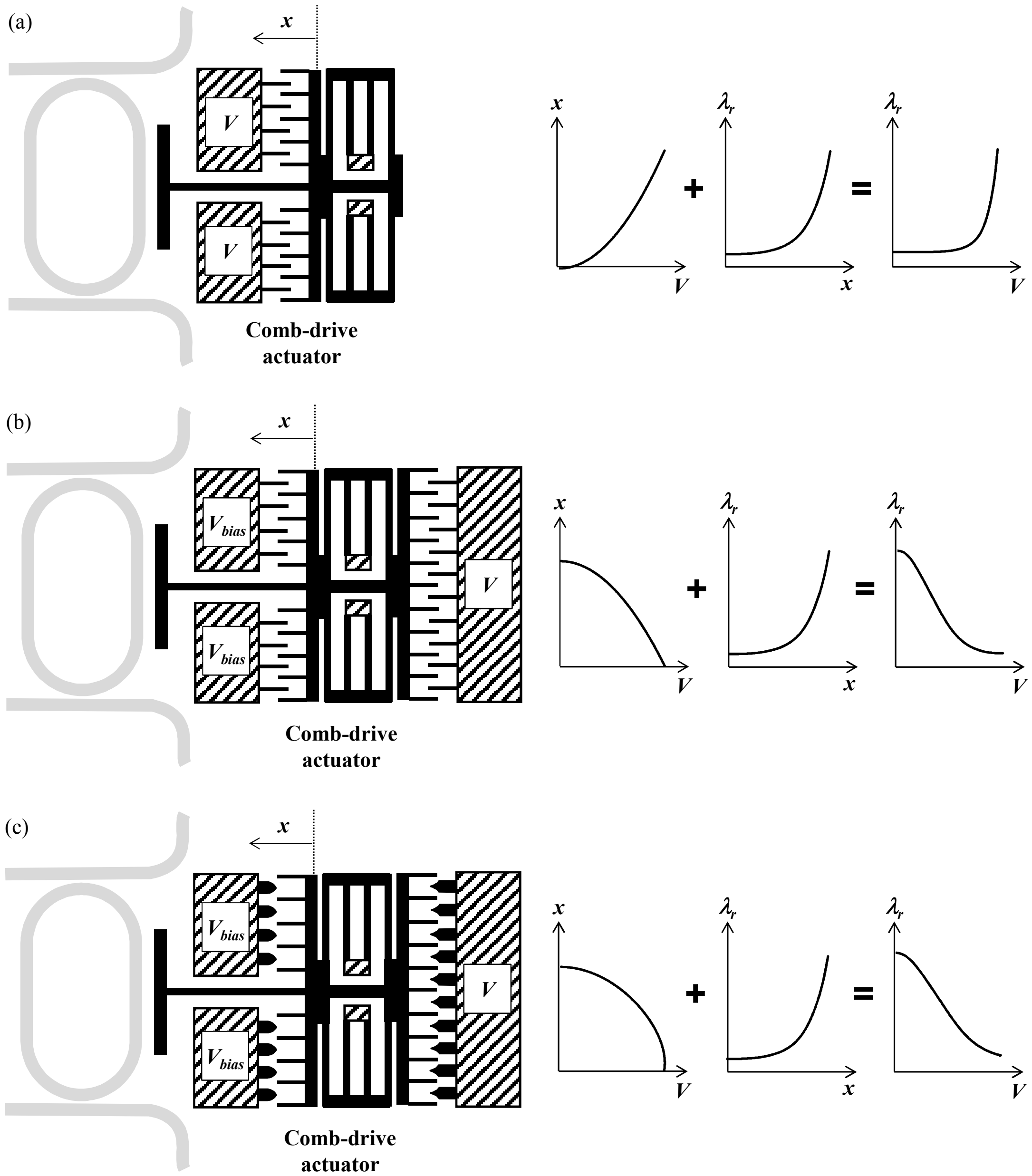

Fig. 2. Schematic diagrams (top views) and tuning profiles of the optical filters with microring resonators and comb-drive actuators: (a) single comb-drive actuator with constant gaps, (b) dual comb-drive actuators with constant gaps, and (c) dual comb-drive actuators with exponentially-varying gaps. λ_r: resonant wavelength of the filter.

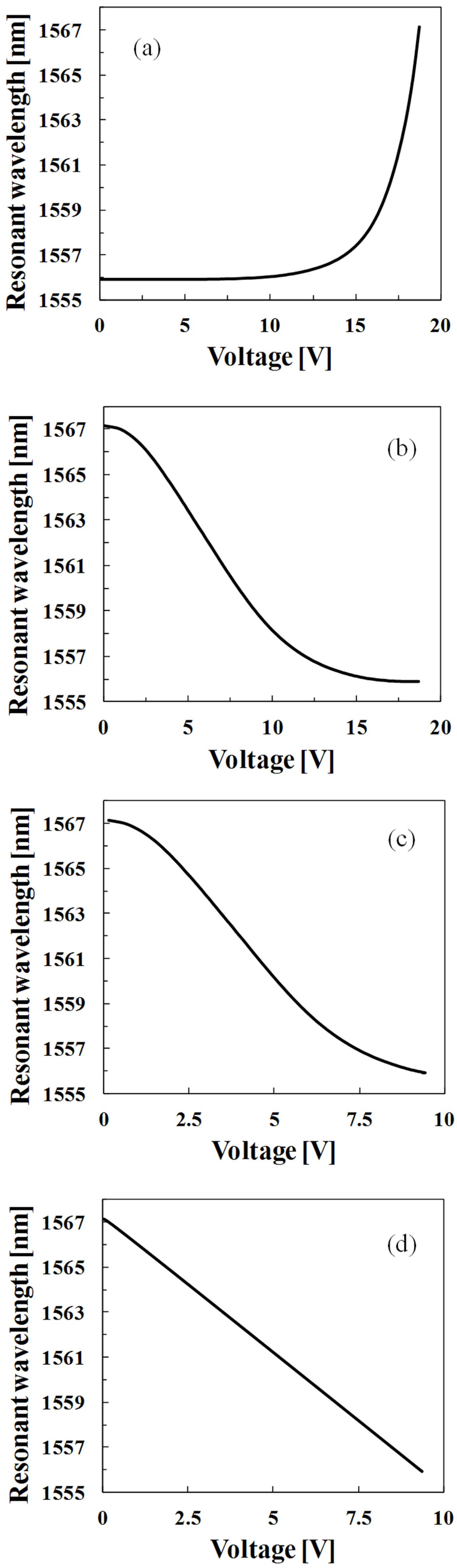

Fig. 3. Simulation results for the mechanically tunable optical filters with comb-drive actuators of (a) figure 2-a, (b) figure 2-b, (c) figure 2-c, and (d) rigorously calculated finger shapes given in fig. 4.

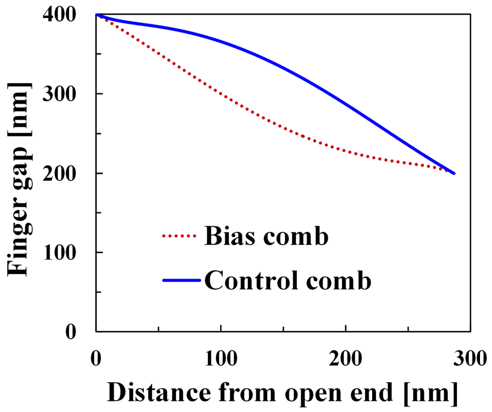

Fig. 4. Calculated finger gaps for linear resonant wavelength-voltage characteristics given in figure 3(d).

resulting resonant wavelength-voltage curve. Since the first term on the left-hand-side of the equation is given by the electromagnetic simulation, the comb finger gaps can be calculated by solving (2), a nonlinear differential equation. Since $d\lambda_r/dx$ is low at small x and high at large x, in order to achieve linear characteristics, it is reasonable to design the both combs with slow-changing gaps for the near side (i.e. near to the index modulator) and fast-changing gaps for the far side (i.e. far from the index modulator). Only the gap changing trends have to be different between two combs: increasing in the bias comb and decreasing in the control comb, from the near side to the far side. This implies implementation of complementary finger gaps for the two combs, which can be expressed as,

$$d_{ctrl}(u) = -d_{bias}(x_{\max} - u) + d_{max} + d_{min}, \qquad (3)$$

where d_{ctrl}, d_{bias}, d_{max}, and d_{min} are finger gaps of control comb, bias comb, maximum separation, and minimum separation, respectively. u is measured from the open end of each comb, i.e. the tip of the fixed finger, and x_{max} is the maximum displacement required for the full sweep. The governing equation of the comb-drive actuators is,

$$\frac{1}{2}\frac{dC_{bias}}{dx}V_{bias}^2 + \frac{1}{2}\frac{dC_{ctrl}}{dx}V^2 - k_s x = 0, \qquad (4)$$

where C_{bias} and C_{ctrl} are the capacitance of the bias comb and the control comb, respectively. By combining (2), (3), and (4), and by taking the first derivative with respect to x, one can achieve,

$$\begin{aligned} d'_{bias}(x) = {} & \frac{1}{x - \dfrac{(d_{max}+d_{min})d_{min}x_{max}}{[d_{bias}(x)]^2}} \\ & \times \Bigg[d_{max} + d_{min} - d_{bias}(x) \\ & + \frac{2a_1\lambda_r'(x)}{C_0}\sqrt{\frac{d_{max}+d_{min}-d_{bias}(x)}{a_1}\left[\frac{d_{min}x_{max}}{d_{bias}(x)} - x\right]}\Bigg], \end{aligned} \qquad (5)$$

where $a_1 = N_f \varepsilon_0 T_f / k_s$. To solve this nonlinear ordinary differential equation, Euler's method can be used. Fig. 3(d) shows the simulation results of the device with the rigorously calculated comb finger shapes, which demonstrates completely linear relationship. Fig. 4 shows the calculated finger gaps for both combs.

IV. CONCLUSIONS

Electromechanical analysis was performed to investigate the device characteristics of the proposed optical filters with microring resonators and mechanical tuning. Various comb-drive actuator designs were explored to optimize the filter characteristics. Study of mechanically tunable optical filters with cascaded rings is underway.

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