J Opt
DOI 10.1007/s12596-016-0371-0

RESEARCH ARTICLE

A concept of integrated acousto-optical switches with multi-modulated-arms in parallel

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Received: 23 February 2016 / Accepted: 5 September 2016

Abstract An analysis is developed for integrated acousto-optical (AO) switches with multi-modulated-arms in a parallel configuration. The analysis shows that an integrated AO switch with multi-arms can improve contrast ratio largely. The optimum SAW phase of closing arms is presented to achieve highest contrast ratio for the integrated AO switches with multi-modulated-arms. A trade-off of fabrication tolerance and higher on/off contrast ratio is discussed, in which, larger number of modulated arms shows a higher on/off contrast ratio, but a stricter fabrication. The research shows that an AO switch with 8-modulated-arms is an optimum structure as an on/off switch with a higher contrast ratio of −75 dB and less number of arms.

Keywords Integrated acousto-optical switches · Multi-modulated-arms · Minimum transmissions (on/off contrast ratio)

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Introduction

Compact AO devices are important components in the integrated optics [1–4]. There are many reports [1–11] about waveguide AO devices, in which, a concept of an integrated AO device with multi-modulated-arms draws large attentions. The concept is proposed to enhance the modulation efficiency by modulating simultaneously multi-arms using a single SAW, which can work as an AO switch for on/off state.

In this manuscript, an analysis is presented for an AO switch with multi- modulated-arms in parallel, which is performed to confirm the feasibility of the concept as AO switches. The influence of number of modulated-arms on the on/off contrast ratio of the AO switches is developed. The SAW phase of closing arms and static phase difference among the arms (determined by the tolerance of optical waveguide fabrication) are discussed for the AO switches with multi- modulated-arms. Some important results are presented for design of the novel AO switches.

Theory

AO switches with multi-modulated-arms shown in Fig. 1 are formed by an input/output waveguides, multi-arms and multi-mode-interference (MMI) splitters. The light is coupled in and then divided into multi-arms by a MMI splitter, which will be combined again into a single output waveguide. The optical power is distributed equally among multi-arms.

We assume that AO switches have N modulated arms, the input power is unity. The arms are aligned perpendicularly to the SAW propagation direction and displaced

Published online: 30 September 2016

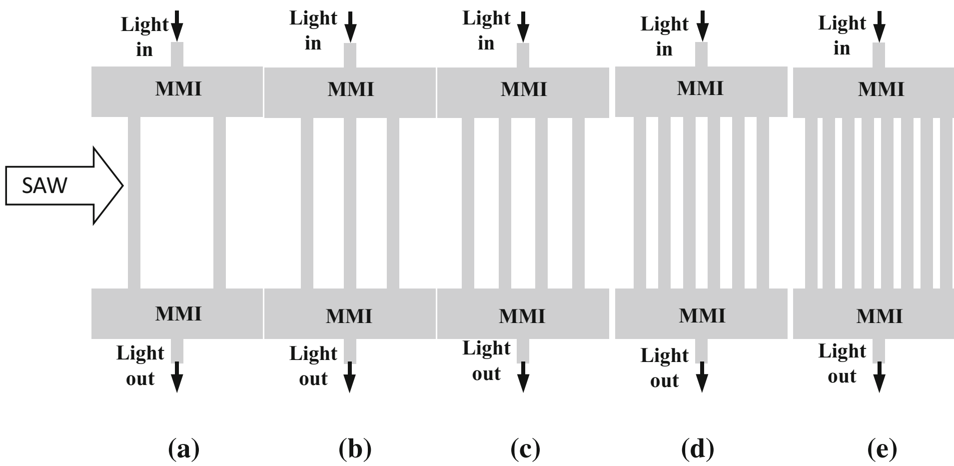

Fig. 1 Sketch of an acousto-optical switch with **a** 2, **b** 3, **c** 4, **d** 6 and **e** 8 arms modulated by SAW in a parallel configuration

laterally equably to experience same phases of SAW (φ_{SAW}) for every arm.

According to theory of MZI devices [4], the optical wave for one arm modulated by SAW will be,

$$\psi_1(t) = \mathrm{e}^{\mathrm{i}[\omega_0 t + \phi \sin(2\pi f_{SAW} t + \varphi_S) + \phi_t]} \tag{1}$$

The optical wave for two arms modulated by SAW will be,

$$\psi_1(t) = \frac{1}{2} * \mathrm{e}^{\mathrm{i}[\omega_0 t + \phi \sin(2\pi f_{SAW} t + \varphi_S) + \phi_t]} \text{ (First arm)} \tag{2}$$

$$\psi_2(t) = \frac{1}{2} * \mathrm{e}^{\mathrm{i}[\omega_0 t + \phi \sin(2\pi f_{SAW} t + (2-1) * \varphi_{SAW} + \varphi_S) + \phi_t]} \text{ (Second arm)} \\ \ldots \tag{3}$$

The optical wave for N arms modulated by SAW will be,

$$\psi_N(t) = \frac{1}{N} \sum_{p=0}^{N-1} \mathrm{e}^{\mathrm{i}[\omega_0 t + \phi \sin(2\pi f_{SAW} t + p\varphi_{SAW} + \varphi_S) + \phi_t]} (N\text{-th arm}) \tag{4}$$

where $\phi = 2\pi\delta nl/\lambda_L$ denotes the light phase shift by SAW, l is the arm length, δn is the refractive index shift induced by SAW, which increase with a square root of the saw power [10], λ_L is a wavelength of a light beam. φ_{SAW} is a SAW phase of two closing arms. φ_S is a phase of SAW at first modulated arm, which depends on the distance between the transducer and the modulated arms. ϕ_t is the static phase difference of the arms, which depends on the tolerance of optical waveguide fabrication.

Results and discussion

Characteristics of AO switches with multi-modulated-arms in parallel

In order to characterize AO switches with multi-arms, we calculate the time- average transmission as a function of optical phase shift by SAW (the optical phase is modulated by SAW, which is proportional to the acoustic power) as shown in Fig. 2. One can observe that the average transmission reduces and reaches a minimum with increase of an optical phase shift, this demonstrates the operation can work as an on/off switch, in which, the maximum of average transmission means on-state of the switch (SAW is turned off), the minimum means off-state of the switch (SAW is turned on).

Characteristics of AO switches for different modulated arms are summarized in Table 1. One can obtain a switch with larger arms has a higher on/off contrast ratio. The needed optical phase shift by SAW modulation for a minimum transmission keeps be a value of 2.405, when the number of arms is larger than 6. Moreover, the on/off contrast ratio of an 8-modulated-arm AO device has reach −75 dB, the value is enough as an AO switch. Hence, an AO switch with 8-modulated-arms can work well as the on/off switch, which has a higher contrast ratio and less

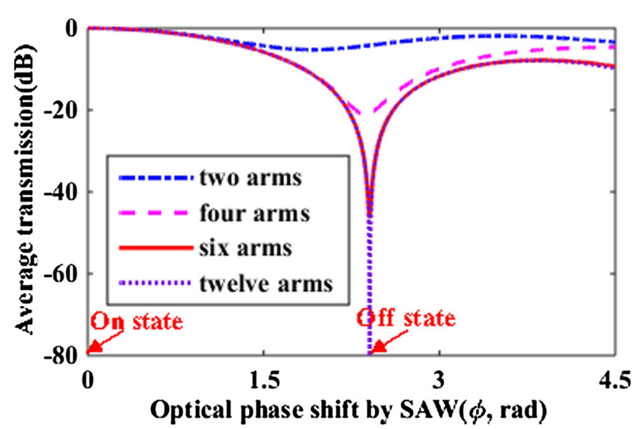

Fig. 2 Average transmission as a function of the optical phase shift (proportional to the acoustic power) by SAW for 2, 4, 6 and 12 modulated-arms. The plot display the operation can work as an optical switch for arbitrary on/off state

Table 1 On/off contrast ration SAW for an AO switch with different arms

Modulated arms (N)	Optical phase shift by SAW modulation	Average transmission (on/off contrast ratio)
2	1.9160	−5.2488
3	2.2120	−11.8824
4	2.3660	−21.0138
6	2.4050	−46.3428
8	2.4050	−75.9845
10	2.4050	−80.8590
12	2.4050	−80.8615

numbers of arms (more numbers of arm mean more complicated structure).

Design of AO switches with multi-arms in parallel

Based on Eq. (4), AO switches with multi-modulated-arms are strictly depended on SAW phase difference of closing arms (φ_{SAW}) and static phase difference of arms (ϕ_t). A SAW propagating phase of closing arms decides on/off contrast ratio of the AO switches. We summarize the optimum SAW phase for highest on/off contrast ratio as a switch with modulated arms as shown in Table 2. An optimum SAW phase is λ_{saw}/N and $(N-1)\lambda_{\mathrm{saw}}/N$ for highest contrast ratio during a period. In the practical case, a larger arm spacing can be chosen for $(m+1/N)$ λ_{saw} or $(m+(N-1)/N)$ λ_{saw} (m is an integer) to avoid the crosstalk of closing arms due to evanescent field coupling. For example, the arm spacing is designed as 2.5 λ_{saw} and 4.5 λ_{saw} for GaAs and SOI platform in the Mach–Zehnder modulator [12].

Table 2 Optimum SAW phase of closing arms for highest on/off contrast ratio of an AO switch with multi-modulated arms

Modulated arms (N)	Optimum SAW phase of closing arms for highest on/off contrast ratio during a period	
2	$\lambda_{saw}/2$	$\lambda_{saw}/2$
3	$\lambda_{saw}/3$	$2\lambda_{saw}/3$
4	$\lambda_{saw}/4$	$3\lambda_{saw}/4$
6	$\lambda_{saw}/6$	$5\lambda_{saw}/6$
8	$\lambda_{saw}/8$	$7\lambda_{saw}/8$
10	$\lambda_{saw}/10$	$9\lambda_{saw}/10$
12	$\lambda_{saw}/12$	$11\lambda_{saw}/12$
…	…	…
N	λ_{saw}/N	$(N-1)\lambda_{saw}/N$

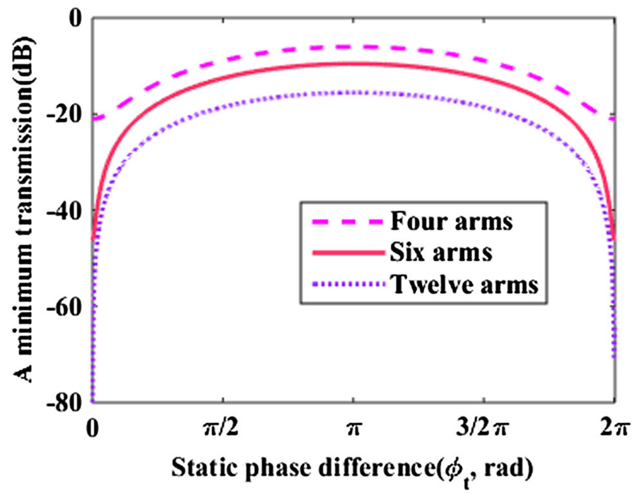

Fig. 3 A minimum transmission (on/off contrast ratio) as a function of the static phase difference among arms (determined by the tolerance of fabrication) for 4, 6 and 12 SAW-modulated-arms

A static phase difference among the arms (ϕ_t) is determined by the tolerance of fabrication, and is also discussed as shown in Fig. 3 for 4, 6 and 12 modulated arms. One can see that the minimum transmissions (on/off contrast ratio) are achieved with a static phase difference of $\phi_t = 0$ or 2π for AO switches with four, six and twelve modulated arms during one period, in which, a switch with 12 modulated arms shows best contrast ratio of −80 dB, however, a little shift from the static phase difference of $\phi_t = 0$ or 2 leads to a quicker drop of the contrast ratio for a switch with 12-arms than the switches with 4 and 6-arms, which means an imperfect fabrication will lead to a more serious influence for more arms due to a quick drop of contrast ratio. In other words, an AO switch with more numbers of modulated arms requires a stricter fabrication.

Conclusion

In this manuscript, a concept of AO switches with multi-modulated-arms is confirmed. A detailed analysis has been developed. An optimum SAW phase for highest contrast ratio is λ_{saw}/N and $(N-1)\lambda_{saw}/N$ for the AO switches during a period. Larger number of modulated arms shows higher on/off contrast ratio, however requires a stricter fabrication. An AO switch with 8-modulated-arms is an optimum structure as an on/off switch with a higher contrast ratio of −75 dB and less number of arms.

Acknowledgments This research was supported by the National Natural Science Foundation of China (Nos. 11574328, 11401585 and 11404009), National Key Scientific Instrument and Equipment Development Projects of China (No. 2014YQ090709), the Beijing Natural Science Foundation (No. 1154009), and the Science and Technology Project of State Grid Corporation of China.

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