A Miniature 1x2 Mechanical Optical Switch with Anti-thermal Design

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Abstract

This paper studies an innovative miniature 1x2 mechanical optical switch with anti-thermal design. Firstly, a novel switch configuration with the line-to-line and fiber-to-fiber alignments is designed. A fiber stopper pivot design is also proposed to reduce the transverse misalignment of fiber tips due to the positioning errors. Then, an included anti-thermal mechanism is proposed by utilizing materials with different thermal expansion coefficients to compensate the axial misalignment due to ambient temperature changes. Finally, the solid model of the optical switch is generated in AutoCAD, and then imported to ANSYS to analyze different thermal responses. According to the analysis results, the misalignment of the fiber tips is reduced and satisfies the insertion loss requirement of Bellcore specifications. This miniature 1x2 mechanical optical switch has characteristics of small size, low-cost and high reliability.

Keywords: Optical switch; Anti-thermal design; Thermal analysis

1. Introduction

Because of the rising popularity of the Internet and personal communication, the fiber-optic networking is becoming more prominent in the high-speed data transmission because its low loss, lightweight, and high bandwidth. The optical switch is essential in an optical communication system because it maps wavelength from input ports to appropriate output ports based on their destination. Bourouha et al. [1] proposed the optic-electro-optic (O-E-O) optical switch. In the O-E-O optical switches, optical signals from the input fiber will be converted into electronic signals first, then through an electronic converter switch to the required output channel. Passing through an electro-optic (E-O) converter, the output optical signals can then couple to the output fiber. However, devices using O-E-O have several drawbacks, such as they require expensive optic-electro (O-E) conversion devices, cross talk is usually high, and the electronics limits the growth in bandwidth. Hedekvist et al. [2] demonstrated the all-optic (optic-optic-optic, O-O-O) switching design is potentially capable of eliminating these disadvantages. Concerning the O-O-O types of the optical switches, the mechanical type still dominates the market. Chang et al. [3] developed a mechanical switching apparatus comprised of an output fiber alignment head with a V-groove and a switching member arranged to pivot between first and second positions. The design of this switching mechanism leads to the bending of the input fiber tip when the fiber is pushed against the V-groove. But, this kind of optical switches are still difficult to meet the requirements of growing up capacity and the Bellcore specifications because they have to adapt to various environments, especially changes of ambient temperature that cause the axial misalignment of the input and output fibers. In order to avoid this situation, a proper anti-thermal mechanism is necessary. Morey and Glomb [4] developed a temperature-compensated optical waveguide light filtering device. The fiber is attached to two compensating members made of materials with different thermal expansion coefficients. In this device, the lengths of both the compensating members and the optical fibers will be changed to compensate the misalignment. Yoffe et al. [5] assembled a passive temperature-compensating package for fiber gratings. The grating is mounted in a package consisting of two materials with different thermal expansion coefficients. A silica tube is used as the low thermal expansion component and an aluminum tube works as the high thermal expansion component. In this design, the aluminum tube was used as the compensating member during ambient temperature changes.

2. Design of a 1x2 mechanical optical switch

The goal of this paper is to design an innovative 1x2 mechanical optical switch. Not only the precision packaging and alignment tasks have to be coped with; the stability due to temperature changes is also an important issue to be addressed.

2.1 The concept design As shown in Table 1, the design specifications of the switch take the temperature cycling tests and insertion loss tests into account. In the standard temperature cycling tests, the switch should be subjected to an ambient temperature change from -40℃ to 75℃. In the standard insertion loss tests, to maintain an insertion loss of less than 1 dB in the Single Mode Fiber (SMF) which its core diameter is 9μm, the axial misalignment and transverse misalignment must be controlled to fall within 30μm and 1μm, respectively (see Peter et al. [6]).

As shown in Fig. 1, a novel switching mechanism for 1x2 mechanical optical switch is designed, which is based on the direct line-to-line and fiber-to-fiber principle. This design eliminates some conventional parts, such as the collimators, turning mirrors [7], and prisms

[8] for structural simplicity, low cost, and low power consumption. In this design, the input fiber is mounted onto a sliding tube. The two output fibers are mounted onto a fiber holder, which is sized by 12×3×0.5 mm^3 with U-groove of 125μm in depth and 250μm in width. The fiber holder is fabricated through MEMS process in order to ensure its accuracy. Two tube stoppers and the sliding tube are assembled in a shaft. A mechanical relay is used to push the sliding tube to stop in the two tube stoppers and switch the input fiber aligning to two output fibers. The configuration of the 1x2 mechanical optical switch is shown in Fig. 2.

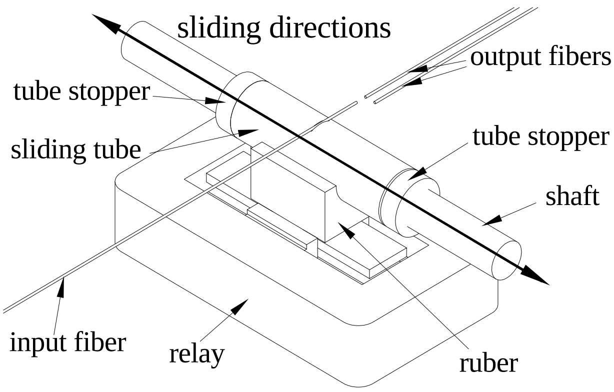


Fig. 1 The switching mechanism of the optical switch

2.2 Fiber stopper pivot design The sliding tube position control is very important in alignment of the input fiber to the two output fibers. As shown in Fig. 3, when the sliding tube is switching input fiber to align the output fibers, the input fiber will be bent due to the sliding tube positioning error. A fiber stopper pivot design is proposed in this paper to reduce the positioning error by using the trigonometric relationship as shown in Fig. 3. Without this design, the transverse misalignment of the input fiber will translate to the same amount to the output fiber, $\delta_1 = \delta_2$, because the input fiber and two output fibers are straight and parallel. In this proposed design, due to the ratio of the arms, *a*/*b*, the transverse misalignment could be significantly reduced in proportion, $\delta_1 = (a/b)\delta_2$.

3. Design of an anti-thermal mechanism

When the ambient temperature is changed, non-uniform thermal expansion of internal components will result in the misalignment of the input fiber tip and the output fiber tip. An anti-thermal mechanism is designed to compensate this misalignment, and thermal analysis is used to prove the design.

3.1 Anti-thermal mechanism design In this paper, as shown in Fig. 4, an anti-thermal mechanism with a high thermal expansion base and a low thermal expansion base is proposed. The sizes of these two bases can be specifically designed to correct the axial misalignment due to ambient temperature changes. The high strength steel alloy can be chosen as the low thermal expansion base material, which its thermal expansion coefficient is 12×10^{-6}/℃. Aluminum alloy can be chosen as the high thermal expansion base material, which its thermal expansion coefficient is 23×10^{-6}/℃. As shown in Fig. 4, the dimensions of the anti-thermal mechanism can be decided using the following equations:

$$\alpha_{hsa} L_1 \Delta T = (\alpha_{aa} L_2 + \alpha_{fh} L_3 + \alpha_f L_4)\Delta T \quad (1)$$

$$L_1 = L_2 + L_3 + L_4 \quad (2)$$

where L_1, L_2, L_3, L_4 are dimensions of the anti-thermal mechanism , ΔT is the ambient temperature change, α_{hsa} is the thermal expansion coefficient of high strength steel alloy (low thermal expansion coefficient material), α_{aa} is the thermal expansion coefficient of aluminum alloy (high thermal expansion coefficient material), α_{fh} is the thermal expansion coefficient of the fiber holder, and α_f is the thermal expansion coefficient of the SMF.

The Based on the thermal balance equations (1) and (2), a set of component sizes are provided for the switch. The material properties of the switch's components are listed in Table 2.

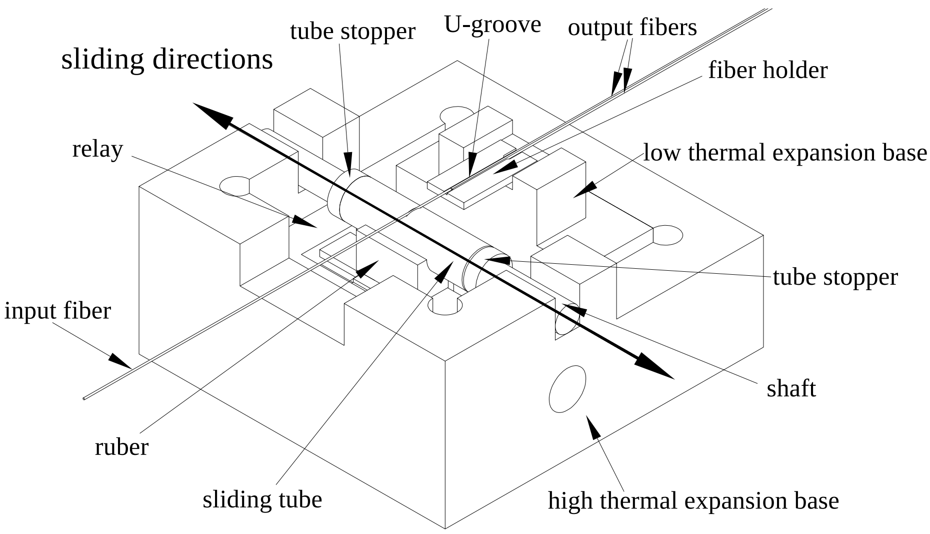


Fig. 2 The configuration of the optical switch

Table 1 Bellcore specifications for the optical switch

Temperature cycling tests	Ambient temperature change from -40 °C to 75 °C
Insertion loss tests	Insertion loss should be less than 1 dB

Table 2 Material properties of switch components

	Switch's components	Young's modulus	Poisson ratio	Thermal conductivity	Thermal expansion coefficient
		(kgf/mm^2)		(W/mm-°C)	(1/°C)
Silica	SMF	7749	0.17	1.4 E-3	0.8 E-6
	Fiber holder				
Al alloy	High thermal expansion base	7300	0.3	10 E-3	24 E-6
Steel alloy	Low thermal expansion base	21122	0.3	51.9 E-3	14.7E-6

Table 3 Thermal deformation in axial direction

	Input fiber tip deformation (μm)	Output fiber tip deformation (μm)	Axial misalignment (μm)
Case 1: temperature from 25°C to 75°C	6.7453	6.8075	0.0622
Case 2: temperature from 25°C to -40°C	8.7690	8.8499	0.0809

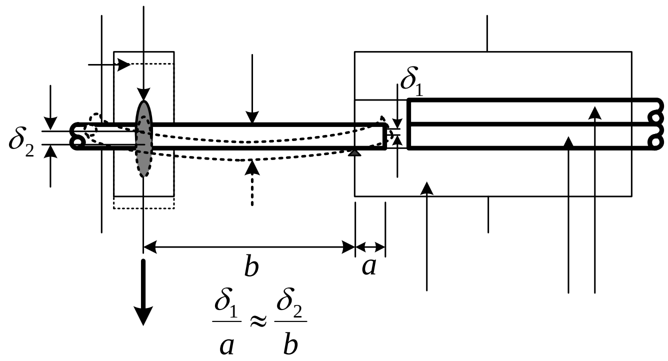


Fig. 3 Principle of the fiber stopper pivot design

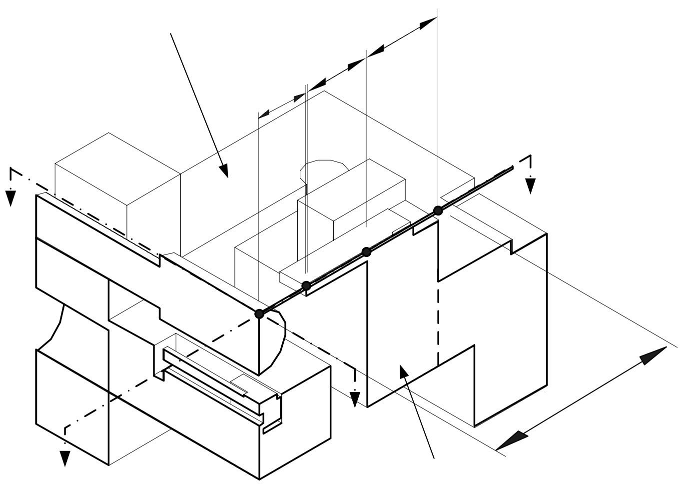


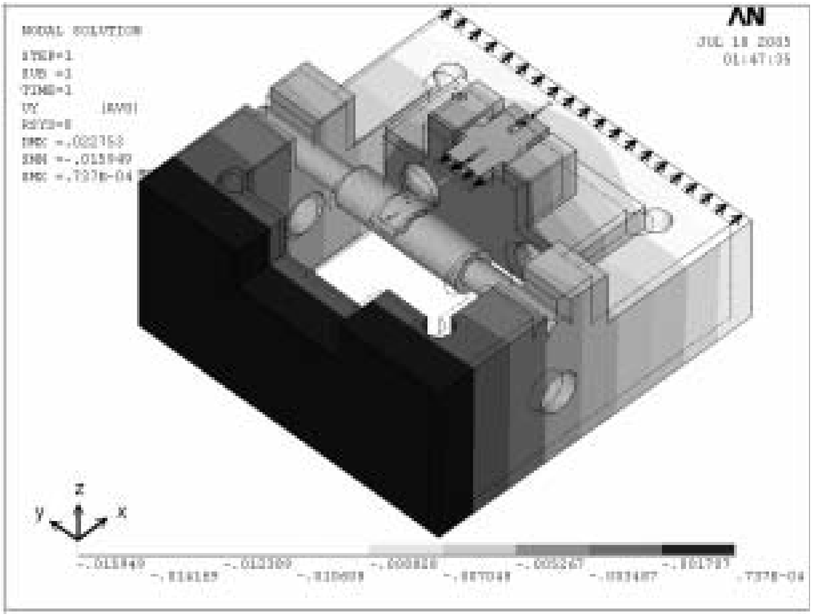
Fig. 4 Cross-sectional view of anti-thermal mechanism

3.2 Thermal analysis of the anti-thermal mechanism

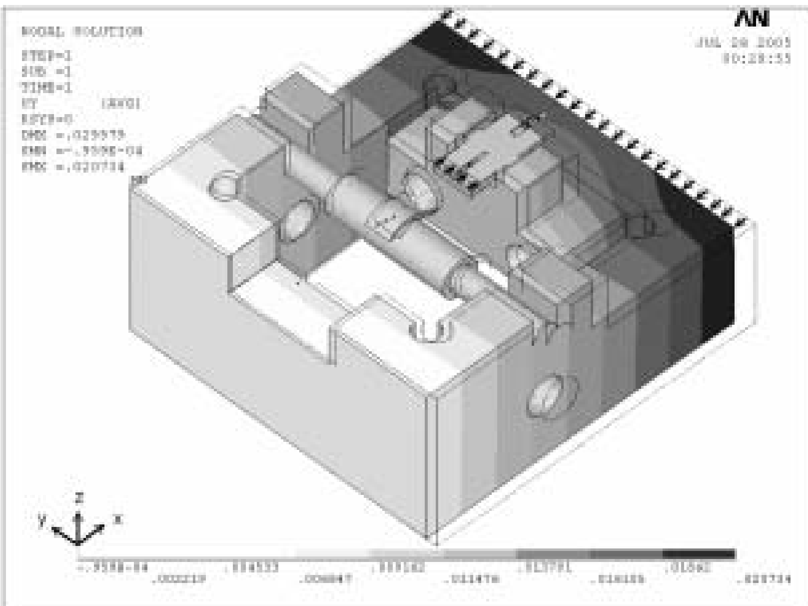
The anti-thermal mechanism design proposed in this paper is proved by computing the thermal deformation in axial direction during ambient temperature changes using ANSYS. The solid model of the anti-thermal mechanism was originally generated in AutoCAD from given design parameters provided by Eq. (1) and (2). The model was exported to an ACIS SAT file by AutoCAD, and then imported to ANSYS to establish the finite element meshes. Then, the solid element type SOLID92 aids in performing the thermal analysis of the anti-thermal mechanism. In the analysis model, two cases of thermal boundary conditions, which are temperature cycling tests, are applied:

(a) Case 1: ambient temperature cycles from 25°C to 75°C
(b) Case 2: ambient temperature cycles from 25°C to -40°C

After applying these boundary conditions to the finite element model, the thermal deformation of the anti-thermal mechanism in axial direction can be computed by ANSYS as shown in Fig. 5(a) and Fig. 5(b). In Fig. 5(a), the low thermal expansion base apart the input fiber from the output fibers in axial direction and the high thermal expansion base compensates the axial misalignment when temperature cycles from 25°C to 75°C. In Fig. 5(b), the low thermal expansion base approaches the input fiber to the output fibers in axial direction and the high thermal expansion base compensates the axial misalignment when temperature cycles from 25°C to -40°C. The thermal deformation result is shown in Table 3. In the case 1, the thermal deformation of input fiber tip and output fiber tip in axial direction are 6.7453μm and 6.8075μm, therefore the axial misalignment of fiber tips is 0.0622μm. In the case 2, the thermal deformation of input fiber tip and output fiber tip in axial direction are 8.7690μm and 8.8499μm, therefore the axial misalignment of fiber tips is 0.0809μm. The analyzed axial misalignments of fiber tips in all cases are much less 30μm and thus the anti-thermal mechanism is proven to reduce the axial misalignment of fiber tips, which can satisfy the insertion loss tests of Bellcore specifications during temperature cycling tests.



(a) Thermal deformation distribution in axial direction of case 1



(b) Thermal deformation distribution in axial direction of case 2

Fig. 5 Thermal deformation of the anti-thermal mechanism in axial direction

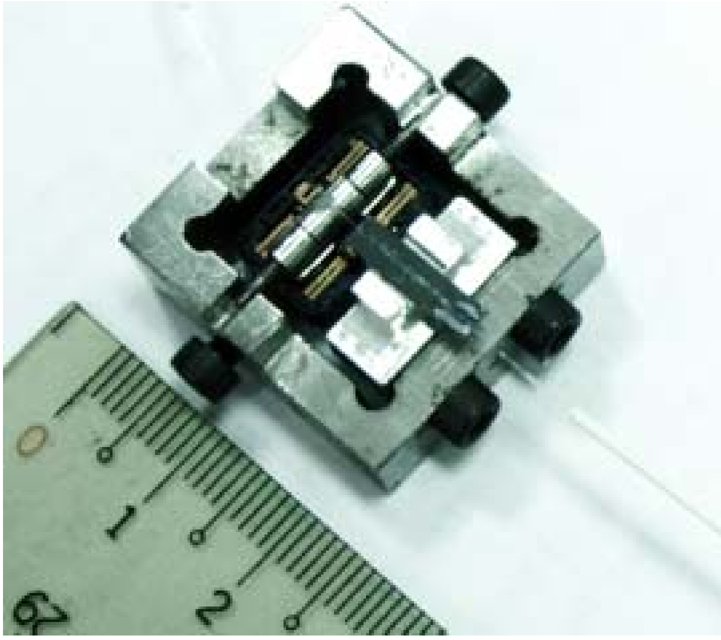


Fig. 6 Photo of the developed 1x2 optical switch

Fig. 6 shows the photo of the developed 1x2 optical switch. There are several advantages of this novel design:

(a) The direct line-to-line and fiber-to-fiber configurations promises less optical loss than other light bending configurations.
(b) A fiber stopper pivot design is proposed to reduce the transverse misalignment of the input fiber and output fiber tips due to sliding tube positioning errors.
(c) An anti-thermal mechanism is designed to compensate the axial misalignment of the input fiber and output fiber tips due to ambient temperature changes. Compared to the traditional optical switches, it omits the collimators and prisms so as to reduce the device size ($25\times26\times12$ mm^3) and cost.

4. Conclusions

This paper studies a miniature 1x2 mechanical optical switch with anti-thermal design. A novel and simple optical switch, which is sized only $25\times26\times12$ mm^3, with line-to-line and fiber-to-fiber configuration is designed. A fiber stopper pivot design is proposed to reduce the transverse misalignment of fiber tips due to the positioning errors. An anti-thermal mechanism is included to compensate the axial misalignment of fiber tips due to ambient temperature changes. The anti-thermal mechanism is proven to use the thermal analysis, which indicated the axial misalignment of fiber tips is 0.0622μm when temperature cycles from 25℃ to 75℃ and the axial misalignment of fiber tips is 0.0809μm when temperature cycles from 25℃ to -40℃. According to the analysis results, the axial misalignment of the fiber tips is reduced and satisfies the insertion loss requirement of Bellcore specifications. This miniature 1x2 mechanical optical switch has characteristics of small size, low-cost and high reliability.

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