Novel MEMS variable optical attenuator

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A novel MEMS variable optical attenuator (VOA), which has completely different attenuation mechanism from those in literatures, is proposed and demonstrated in this paper. The basic operation principle is that the optical power coupled between two initially aligned single-mode fibers will be continuously attenuated while the end of one of the fibers is deflected from the initial position. A micromachined solenoid type inductor with a U-shaped permalloy magnetic core is used to attract the deflectable fiber that has a permalloy coat on its end. To fabricate the multi-layer three-dimensional inductive component, a new UV-LIGA process for thick photoresists is developed, combining advantages of both SU-8 and AZ-4000 series photoresists. The inductive component is approximately 1.7 mm$\times$1.3 mm$\times$50μm in size and has a low resistance value ($\sim$ 2.1Ω). The whole size of the VOA before packaging is 30 mm$\times$2 mm$\times$0.6 mm. The first prototype shows less then 3-dB insertion loss at 0-dB attenuation and nearly 40-dB attenuation range with less than 20 mW electrical input power at wavelength 1550 nm.

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Variable optical attenuator is an important component used in advanced lightwave networks and subsystems. Optical subsystems in lightwave networks operate over a broad range of optical power levels, ranging from those emanating from high-power transmitters and amplifiers ($>$ 20 dBm), to weak signals arriving at receivers (< -30 dBm). Furthermore, systems engineering may place serious requirements on the optical power dynamic range from the source and at the receivers, illustrated by the range of span losses in an optical line system ($\sim 0-33$ dB) or the numbers of channels present in a wavelength-division-multiplexed (WDM) system ($1- > 100$). Fixed optical attenuators are frequently used to increase the loss of short optical fiber spans to reduce the power impinging on the receiver detector, and variable attenuators are proposed for use in amplified WDM networks to regulate signal powers. High-speed variable optical attenuators might also be used for transient suppression in these networks. Finally, erbium-doped fiber amplifiers (EDFAs) are commonly designed for interstage variable attenuators acting as gain-tilt equalizers[1].

Various variable optical attenuators have been developed using conventional sliding block mechanical systems, side-polished fiber devices, Faraday rotators, waveguide thermooptic devices, and microelectromechanical systems (MEMS)[2]. Conventional sliding-block mechanical attenuators have excellent optical characteristics, but they are bulky, costly, and adjust slowly (0.5 – 1 s). Waveguide thermooptic attenuators can respond in ms time, but cannot achieve the high dynamic range with low insertion loss[1]. It seems that MEMS attenuators rising in recent years are more promising than the others because of the advantageous characteristics of MEMS technology. In fact, the large amount of application researches of MEMS in optics, such as those on micro lens, micro mirrors, switches, attenuators, and free-space micro optical bench, have raised another direction called micro-optic-electromechanical system (MOEMS). MEMS variable optical attenuators in literature can be classified into sliding-vane type[1,3,4], tilt-mirror type[5,6], and MARS type[7] according to the attenuation mechanism.

In this paper, we introduce a new type of MEMS variable optical attenuators, which may be actuated in various methods. The one proposed in this paper uses electromagnetic actuation with a micromachined 3-D solenoid inductor which also is a recent research focus[8,9].

Figure 1 shows a schematic diagram of the proposed variable optical attenuator. It consists of fiber alignment structures, a fixed single mode fiber, a deflectable single mode fiber, and a microactuator. The alignment structures include two micromachined grooves, e.g. V-grooves anisotropically etched on the surface of silicon substrate and disposed in a straight line, and they are separated with their ends opposite by a wider groove which provides room for the deflectable fiber to deflecting. The fixed fiber is completely fastened in one of the grooves while the deflectable fiber is fixed in another groove partially with a long front section suspending over the wider groove as a cantilever beam. Beside the deflectable fiber there is the microacuator. The two

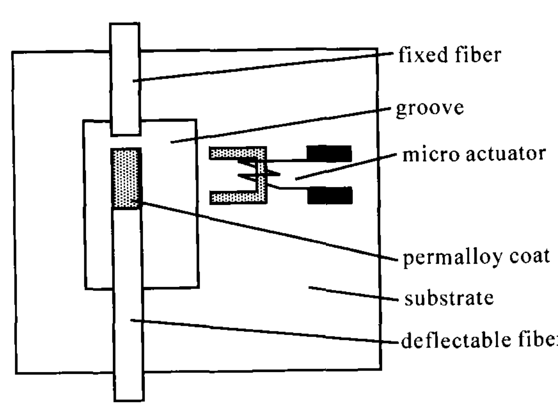

Fig. 1. Schematic diagram of the proposed variable optical attenuator.

fibers, any one for input and the other for output, are well aligned initially so that the insertion loss is very low. When electric power is applied to the microactuator, it will deflect the cantilever beam fiber to a corresponding position and the light coupled from one fiber to the other will decrease with the increasing fiber deflection. As for the microactuator, there are several options. In this paper, we use an electromagnet. This three-dimensional electromagnet is microfabricated on the surface of the substrate and locates on the same level as the axis of the fibers does. There is a permalloy coat on the outside of the front part of deflectable fiber so that the fiber can be attracted by the electromagnet when an electric current runs in the electromagnet coil.

The attenuation is based on the following principle of fiber optics. Gaussian beam can be an approximation to the optical fiber mode. When the axes of two coupled single mode fibers are parallel but not in one line, as shown in Fig.2 (a), the optical power loss can be written as

$$L_d = -10 \lg e^{-\left(\frac{d}{\omega}\right)^2} \mathrm{dB}, \quad (1)$$

where ω is the mode-field diameter of single mode fiber and is function of core diameter a, core refractive index n_1, cladding refractive index n_2, and signal wavelength λ.

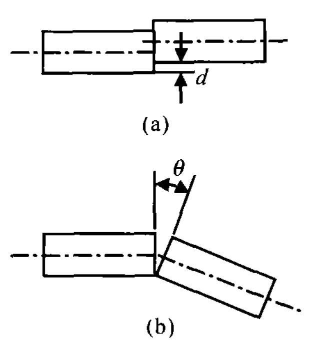

Fig. 2. Fiber-to-fiber coupling.

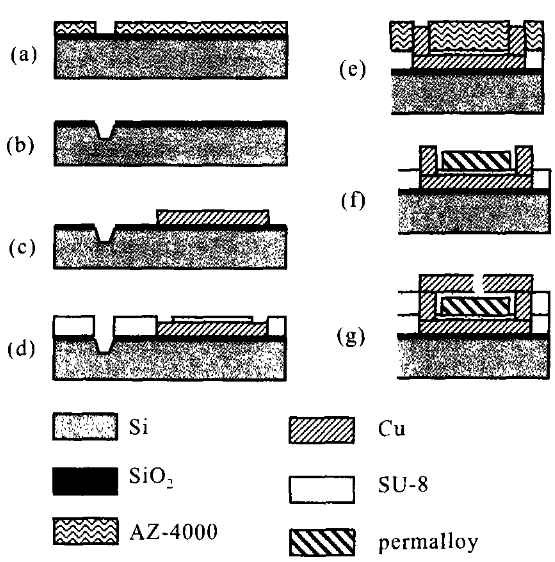

Fig. 3. Fabrication steps. (a) V-grooves patterning. (b) Etching in BHF and KOH sequentially. (c) Electroplating bottom conductor lines. (d) Via opening. (e) Cu via electroplating. (f) Magnetic core plating. (g) Top conductor lines plating.

When one single mode fiber tilts to an angle θ with respect to the other, as shown in Fig. 2(b), the transmitting optical power loss can be expressed as

$$L_\theta = -10 \lg e^{-(\pi n_2 \omega \theta / \lambda)^2} \mathrm{dB}. \quad (2)$$

Actually, both the factors illustrated above contribute to the attenuation in this type of attenuators. But the latter can be ignored because the deflection of the cantilever is so tiny comparing with its length that the angle θ is very small. So here the whole optical power loss can be approximately estimated only according to Eq. (1).

To fabricate the newtype variable optical attenuator, a new process was developed consisting of UV-lithography of both thick positive photoresist (AZ-4000 series) and negative photoresist (SU-8 series), electroplating of both copper and permalloy, and assembly. Figure 3 schematically shows the fabrication steps. First a thin positive photoresist layer was spun on oxidized silicon wafers and patterned to form V-grooves' etching mask resisting BHF. After pattern was transferred to silica layer in BHF, the photoresist layer was removed in acetone and the wafers were etched in 40% KOH solution for an appropriate time to form appropriately deep isosceles trapezoid grooves instead of complete V-grooves. Actually, complete V-groove can introduce greater stress concentration and difficulty for the next steps and thus is not necessary for fiber alignment structure. When photoresist is spun on a wafer with grooves, the areas of the coat surface near the grooves are slopes down to the grooves edges so that the process building structures beside grooves can hardly be continued. We have developed a technique to overcome this difficulty.

When the grooves were in place, we began micromachining three-dimensional horseshoe-shaped electromagnet lying beside the grooves on the substrate. First a seed layer of Cr(20 nm)/Cu(80 nm) was deposited by sputtering and then a thick positive photoresist layer was spun and patterned to form electroplating molds for the bottom conductor lines using standard UV photolithography. Next, 10 μm thick Cu was electroplated in the molds. Then the photoresist was removed and seed layer was etched away. A negative photoresist (SU-8 series) was spun on the bottom conductors to form an insulation and support layer and the via was opened simply using UV photolithography. This technique has some advantage compared with hard-curing positive photoresist. After that a new seed layer was deposited on top of the negative photoresist. In the similar way as the bottom conductors, the via connections and a permalloy magnetic core were electroplated, respectively. Finally the top conductor lines were electroplated after a second insulation and support layer had been formed. Figure 4 shows the SEM photograph of the fabricated electromagnet beside a groove. The magnetic core is in the lower layer, so it can not be seen in the photograph. The footprint of the electromagnet is approximately 1.7×1.3 mm^2.

After micromachining, we aligned two single mode optical fibers (8-μm mode diameter, suited for 1300 – 1550 nm signal wavelength). The end-faces were spaced only

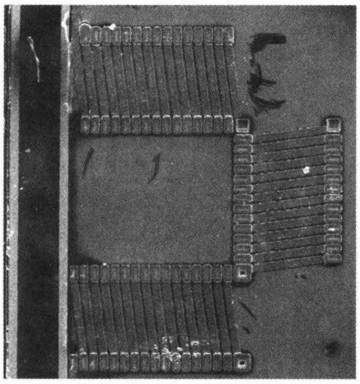

Fig. 4. SEM photograph of the microfabricated electromagnet deside a groove.

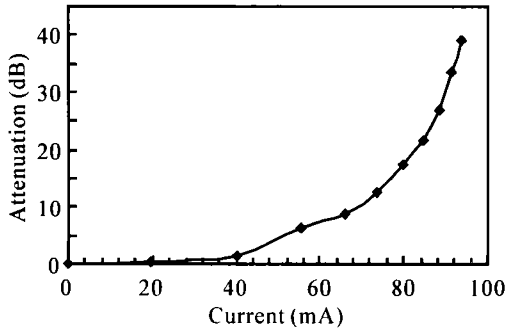

Fig. 5. Static attenuation/current characteristics of the variable optical attenuator.

a few μm to reduce fiber-to-fiber coupling loss. The fibers were then glued in place. The front part of the deflectable fiber was coated with permalloy previously. The whole size of the device before packaging is $30 \times 2.5 \times 0.6$ mm^3.

After completing the first prototype fabrication and assembly, partial characterization of the electromagnet and the attenuator was performed. The measured resistance of the electromagnet coil is 2.1 ohms. This low DC resistance meets the need for low driving voltage, low power consumption and low temperature rise.

To measure the attenuation performance, a laser diode at 1550 nm was used as the light source and the optical output was observed with a power meter and photodetector. The insertion loss of the first prototype at 0-dB attenuation was 2.7 dB. This can be greatly reduced simply by initially aligning the fibers better. The results would represent those for other wavelengths for which the single mode optical fibers can transmit because this device is wavelength-independent due to its optical principle (see Eq. (1)). Then electric power was applied to the attenuator to measure its attenuation range. Figure 5 shows the optical attenuation as a function of the applied current. The optical attenuation increases monotonously, though not linearly, with the increasing driving current. The dynamic attenuation range is nearly 40 dB and the applied electric power is less than 20 mW.

Tests have been conducted repeatedly four times in one month and there is no observable difference between the results. The attenuator has good repeatability and stability because the materials used in the device, such as silica optical fiber, permalloy and copper are stable, and the deflection of the fiber and the magnetization in permalloy in action are designed to be very small. More tests will be performed later.

In conclusion, we proposed a new type of MEMS variable optical attenuators whose attenuation mechanism is completely different from those in literatures. They may be actuated in various methods. Second, we realized the new type VOA using electromagnetic actuation of a micromachined solenoid type inductor with a U-shaped permalloy magnetic core. Its low insertion loss below 3 dB, great dynamic range about 40 dB, low power consumption less than 20 mW, and its inherent advantage such as high accuracy, high return loss, low wavelength and polarization-dependence loss, and more important, the possibility to form an array of VOA on chip, make it an ideal candidate for the power management in complex WDM networks.

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