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# Super High-Performance MEMS Fiber Optic Variable Optical Attenuator (VOA) for Aerospace & Commercial Applications

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## ABSTRACT

Fiber-optic variable optical attenuators (VOAs) are required for light power control in numerous applications such as test and instrumentation, optical fiber telecommunications, industrial fiber-optic sensing, biomedical imaging and sensing, and photonic signal processing for antennas and radar systems. The requirements for the VOA, such as dynamic range and resolution, vary depending on the application. A VOA can demonstrate high end performance when it possesses critical attributes like super resolution precision and high dynamic range. Reported in this paper is the demonstration of a hybrid analog-digital fiber-optic VOA design that employs microelectromechanical systems (MEMS) technology. The VOA demonstrates simultaneously a super high controlled dynamic range of 81 dB as well as super 0.1 dB resolution attenuation controls. Proof-of-concept experiments exhibit an optical loss of 2.5 dB and C-band operations.

**Keywords:** Variable Optical Attenuator (VOA), Digital Micro-Mirror Device (DMD<sup>TM</sup>), fiber-optics.

## 1. INTRODUCTION

Extensive use of optical fibers in science, industry and medicine has led to the need for realizing a Fiber-optic Variable Optical Attenuator which can control light power according to the requirements of the application. Some applications include optical fiber communications, industrial fiber-optic sensing, biomedical imaging and sensing, and photonic signal processing for antennas and radar systems. The requirements such as dynamic range and resolution vary with different applications and the VOA should have the capability to meet those requirements with precision and repeatability. VOAs designed via optical micro-mirrors built using micro-electromechanical systems (MEMS) technology have proven to be an attractive VOA technology. These VOAs can be divided into two categories of analog and digital VOAs. The analog design VOA<sup>1,2</sup> involves a change in an analog drive signal (e.g., voltage level driving a micro-mirror) that causes an analog motion of the micro-optic (e.g., tilt change) to realize a smooth analog change in the light power level exiting the VOA. Such a VOA is highly effective in producing a large attenuation dynamic range by increasing the range of analog motion of the micro-optics. The analog VOA, however, faces a dilemma where resolution of control suffers at the expense of increasing dynamic range. From a physical constraints point-of-view, this dilemma exists as the physical positioning of the micro-optics has its fundamental limits, apart from the fact that the resolution of the driving signal controls increases greatly with the need for improved resolution at all settings of the VOA dynamic range. The second category of VOAs is the digital VOA<sup>3,4</sup>. Here, advantage is taken of the fixed spatial map of a light beam exiting a single mode fiber (SMF). The light beam transmission or reflection area is divided into discrete sub-zones such as using many tiny micro-mirrors that fill the spatial extent of the beam. In this case, beam attenuation is achieved via digital control of the individual micro-mirrors. A micro-mirror is considered to be in "off state" when it directs light to the exit SMF where as it is taken to be in "on state" when it directs light away from the exit SMF. Thus the VOA design with digital control of micro-mirrors tilt states provides 100 % repeatable attenuation controls over the designed dynamic range of the VOA. The specific dynamic range available depends on various factors of the digital micro-mirror chip such as digital tilt angle states, device fill factor, and distance of chip from the exit SMF. In essence, the digital VOA provides excellent digital precision attenuation resolution and repeatability; nevertheless, has limitations on the high (e.g., > 60 dB) dynamic range front. This paper demonstrates a VOA that solves the present VOA dilemma of simultaneous high dynamic range and high resolution controls.

## 2. THE HYBRID ANALOG-DIGITAL VOA DESIGN

Recently, a hybrid analog-digital VOA design was proposed by N. A. Riza<sup>5</sup> to obtain simultaneously both high dynamic range and high resolution. Fig.1 shows an example implementation of this technique for a MEMS VOA with independent input and output fibers. Light to be attenuated is fed to a fiber lens FL<sub>1</sub> through a single mode fiber (SMF). The light exits the fiber lens FL<sub>1</sub>, follows Gaussian expansion and falls on the Texas Instruments (TI) Digital Micro-mirror Device (DMD<sup>TM</sup>). After reflection from the DMD<sup>TM</sup> the light is coupled back into a second fiber lens FL<sub>2</sub>. The fiber lenses FL<sub>1</sub> and FL<sub>2</sub> are of the self-imaging type where the minimum beam waist diameter of  $2w_0$  occurs at a distance  $d_L$  from the fiber lens surface. The DMD<sup>TM</sup> is placed so that it is at distance  $d_L$  from both fiber lenses FL<sub>1</sub> and FL<sub>2</sub>. Hence, the DMD<sup>TM</sup> plane is at the minimum beam waist location of fiber lenses FL<sub>1</sub> and FL<sub>2</sub>. This leads to a condition of near perfect self-imaging between the two fiber lenses. Using the self-imaging free space fiber-to-fiber coupling geometry produces minimal optical loss<sup>6</sup>. With all micro-mirrors in the device set to “off state”, the device angular position and horizontal position are optimized to an initial tilt and translation zero state where the light from the input fiber is reflected optimally into the fiber lens FL<sub>2</sub>. This coupled light then exits the VOA via an output SMF. Details on the design and working of the DMD<sup>TM</sup> are described in an earlier reference<sup>7</sup>. The second fiber lens FL<sub>2</sub> is mounted on a fine tilt stage whose angular tilt can be smoothly varied to cause the reflected beam to become angularly misaligned with the fiber lens. In addition, fiber lens FL<sub>2</sub> is also linked to a translation stage that allows FL<sub>2</sub> to translate in the x-direction and hence introduce misalignment-based coupling loss. As shown in Fig. 1, translation of the fiber lens FL<sub>2</sub> acts as a sliding knife-edge cutting perpendicularly across the light beam cross-section projected by the DMD<sup>TM</sup>. On the other hand, fine analog tilt motion of FL<sub>2</sub> continues to keep the entire DMD<sup>TM</sup> reflected optical beam cross-section on the FL<sub>2</sub> entrance face. Thus, analog tilt and translation motion controls of FL<sub>2</sub> provide the analog mechanisms to attenuate the input light and hence realize an analog VOA. In effect, one can reach any desired coarse attenuation setting of the VOA using these analog mechanisms. Once the given coarse attenuation setting is achieved, the digital-mode of the VOA steps into action. Specifically, the “on state” of the micro-mirrors in the DMD<sup>TM</sup> chip are set to arrive at the desired super-resolved attenuation setting. Because there can be over a thousand of digitally set micro-mirrors in the given SMF-fed optical beam incident on the DMD<sup>TM</sup>, over ten bits of attenuation fine control is readily achievable for the VOA for any given coarse attenuation analog setting. Thus, a hybrid analog-digital design MEMS VOA is realized that can simultaneously achieve high dynamic range and high-resolution repeatable attenuation controls.

## 3. EXPERIMENTAL DEMONSTRATION

The hybrid VOA design of Fig.1 is demonstrated in the laboratory using a 1550 nm laser source. Optical power measurements are taken using a power meter and an optical spectrum analyzer. The measured optical losses for the VOA design segments are as following: 0.18 dB fiber lens FL<sub>1</sub>; 0.16 dB fiber lens FL<sub>2</sub>; 0.01 dB fiber-to-freespace coupling; 1.9 dB DMD<sup>TM</sup> chip due to fill factor, diffraction and micro-mirror reflectivity. The fiber lenses FL<sub>1</sub> and FL<sub>2</sub>  $1/e^2$  beam waist radius is  $w_0 = 0.22$  mm and the self-imaging distance used is  $d_L = 60$  mm. The total VOA loss for its zero attenuation setting is measured to be 2.25 dB with a  $<0.05$  dB polarization dependent loss (PDL) and telecom C-band operations. Fig.2 shows normalized attenuation data for the VOA obtained using pure analog tilt control of the fiber lens FL<sub>2</sub>. Measurements taken indicate a smooth 53 dB optical attenuation dynamic range obtained by tilting the fiber lens through an angle of  $0.23^\circ$ . Thus, fine tilt motion of FL<sub>2</sub> can deliver a wide analog dynamic range for the proposed hybrid design VOA. Next, three examples are considered for demonstration of VOA hybrid analog-digital mode operation with both high dynamic range and high-resolution attenuation.

For the first example, a low attenuation range value of 3.5 dB attenuation is chosen and the setting is achieved by analog only tilt angle controls. Then the digital mode of the VOA is switched on using a column-by-column micro-mirror addressing mode. As shown in Fig. 3(a), switching 14 micro-mirror columns to the “on state” changes the attenuation setting from 3.5 dB to 4.38 dB, a 0.88 dB attenuation change. This data indicates an average 0.063 dB attenuation resolution per column of micro-mirrors. The same procedure is repeated for the second and third examples of the hybrid VOA in the mid and high attenuation range by choosing values of 36 dB and 52.5 dB, respectively. Fig. 3(b) shows that switching 14 micro-mirror columns to the “on state” changes the attenuation setting from 36 dB to 38.48 dB, a 2.48 dB attenuation change. This data indicates an average 0.177 dB attenuation resolution per column of micro-mirrors. Similarly, Fig. 3(c) shows that switching 14 micro-mirror columns to the “on state” changes the attenuation setting from 52.5 dB to 56.86 dB, a 4.36 dB attenuation change. This data indicates an average 0.311 dB attenuation resolution per column of micro-mirrors. Note that each micro-mirror column used is presently designed via software control to contain 88 micro-mirrors. Thus on/off control of individual micro-mirrors, within a column leads to even higher resolution

attenuation controls. Because the micro-mirrors operate in a digital fashion, these digital-mode attenuation settings are repeatable.

The hybrid analog-digital VOA operation results in a high dynamic range as once the analog tilt mode provides the maximum analog attenuation, the DMD™ micro-mirror columns are deployed to achieve more attenuation. Data in Fig. 4 shows that for the chosen analog high attenuation setting of 52.5 dB (third example of hybrid VOA), switching 70 of the DMD™ micro-mirror columns covering the near null-to-null beam area to “on state” increases the VOA attenuation and leads to a higher hybrid VOA dynamic range of 81 dB. Thus, the illustrated data in Fig. 3(a-c) and Fig. 4 show the versatility of the hybrid VOA to simultaneously produce precise attenuation controls over a super-wide dynamic range using the concept of hybrid analog plus digital micro-mechanics.

Fig. 5 shows normalized attenuation data for the VOA obtained using the alternative pure analog translation control of the fiber lens FL<sub>2</sub>. Measurements indicate a 60 dB optical attenuation dynamic range obtained when the fiber lens FL<sub>2</sub> is translated through a 1 mm distance along the x-direction. Thus, pure analog translation provides another analog attenuation mechanism for the hybrid analog-digital VOA operation.

The hybrid VOA operation can be compared when using the two different analog modes, i.e. tilt of FL<sub>2</sub> versus translation of FL<sub>2</sub>. Note that when translation of FL<sub>2</sub> is used for analog attenuation, the available digital attenuation states reduce in number. This happens because as the lens moves, it cuts across the beam cross-section and captures a portion of the light beam, very much like a moving knife-edge. The total number of digital micro-mirrors on the DMD™ over which the light beam falls can be divided into useful and non-useful segments. The useful digital micro-mirrors control the light captured by FL<sub>2</sub> whereas the non-useful micro-mirrors control the light not captured by FL<sub>2</sub>. As fiber-optic VOA operation is introduced via attenuation of the captured light, it can be concluded that the number of available digital attenuation micro-mirrors/states reduce with increasing translation steps of the fiber lens FL<sub>2</sub>. Nevertheless, translation of FL<sub>2</sub> can be used for optimization and calibration of the VOA. On the contrary, FL<sub>2</sub> tilt induced attenuation does not pose this issue as with increasing tilt angle of FL<sub>2</sub> the intensity of the beam captured by FL<sub>2</sub> reduces but the beam shape and profile remains intact over the entire lens entry face. Thus, all of the digital micro-mirrors on the DMD™ lying in the beam cross-section are available for digital attenuation. This leads to a high number of digital attenuation states and thus a high resolution for the hybrid VOA operation when using the tilt mode of FL<sub>2</sub>.

## 4. CONCLUSION

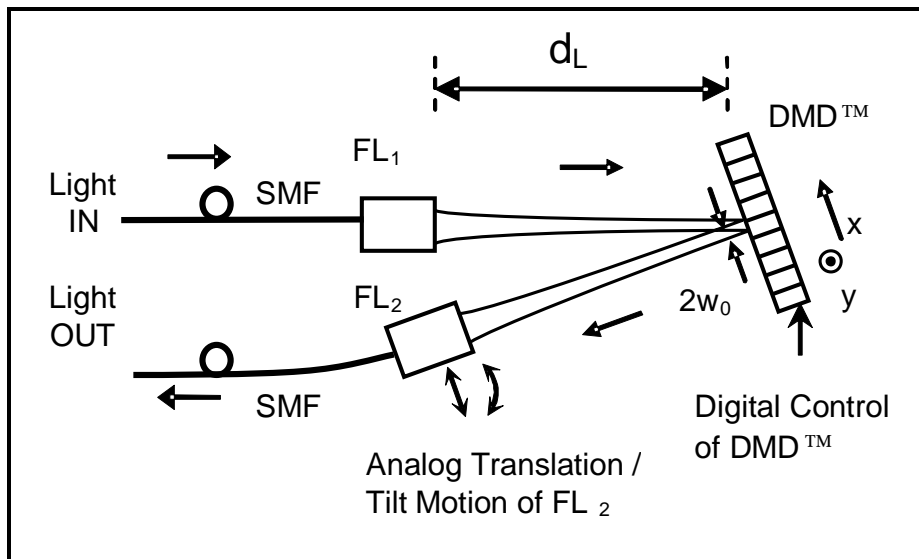
The principles of a novel hybrid design MEMS VOA with independent input and output fibers has been successfully demonstrated indicating both high 81 dB dynamic range and high 0.1 dB resolution controls with even a super-resolution (e.g., <0.0035 dB) capability<sup>8</sup>. The hybrid VOA demonstrated a 2.25 dB optical loss, a < 0.05 dB PDL, and C-band operation. Optimal operation of this VOA can be achieved via a look-up table of attenuation weights set for a variety of analog and digital control states. A single input/output fiber hybrid VOA design is also possible using a fiber-optic circulator<sup>9</sup>. Future work relates to optimization of the VOA module for insertion into standard photonic test and instrument hardware.

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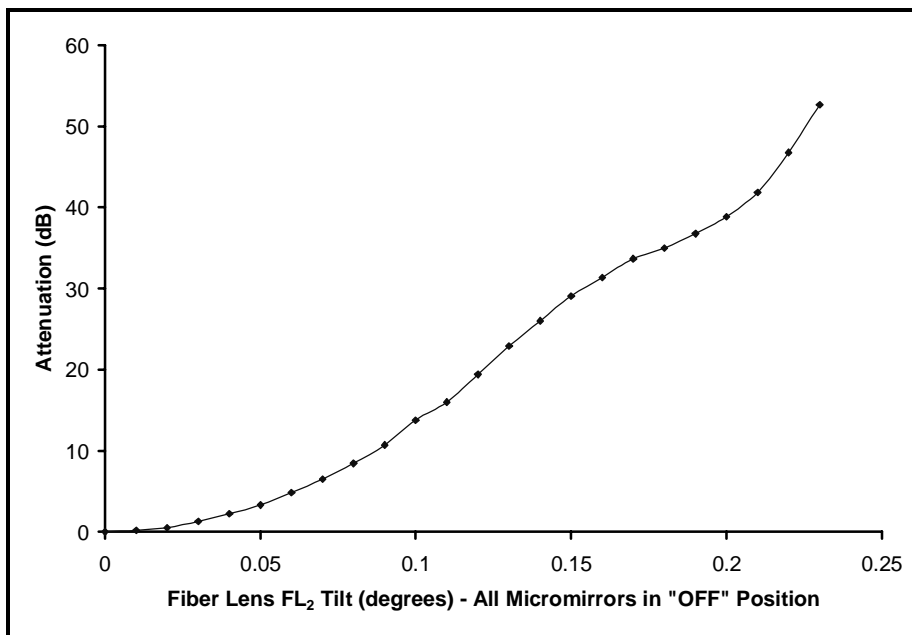
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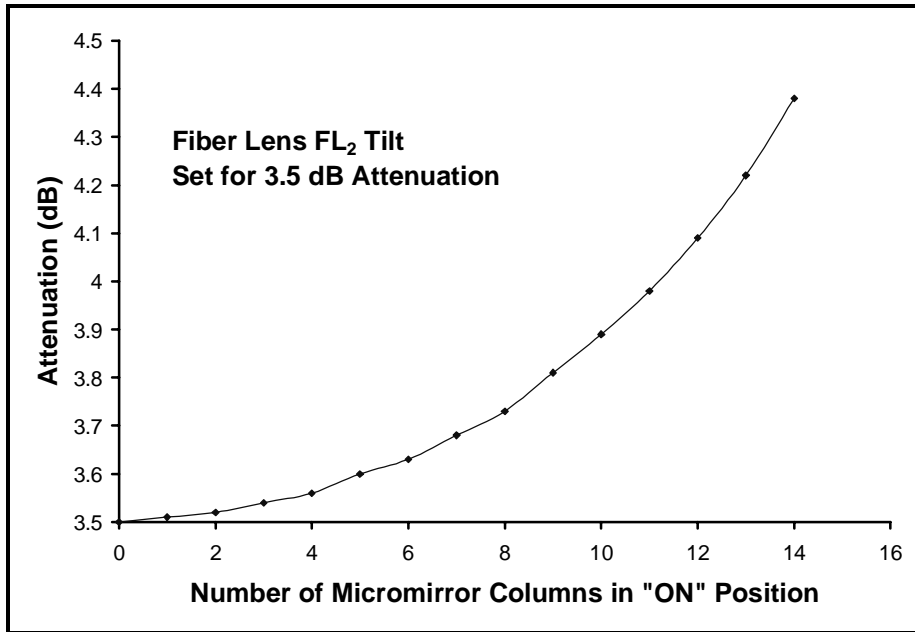
**FIGURES**



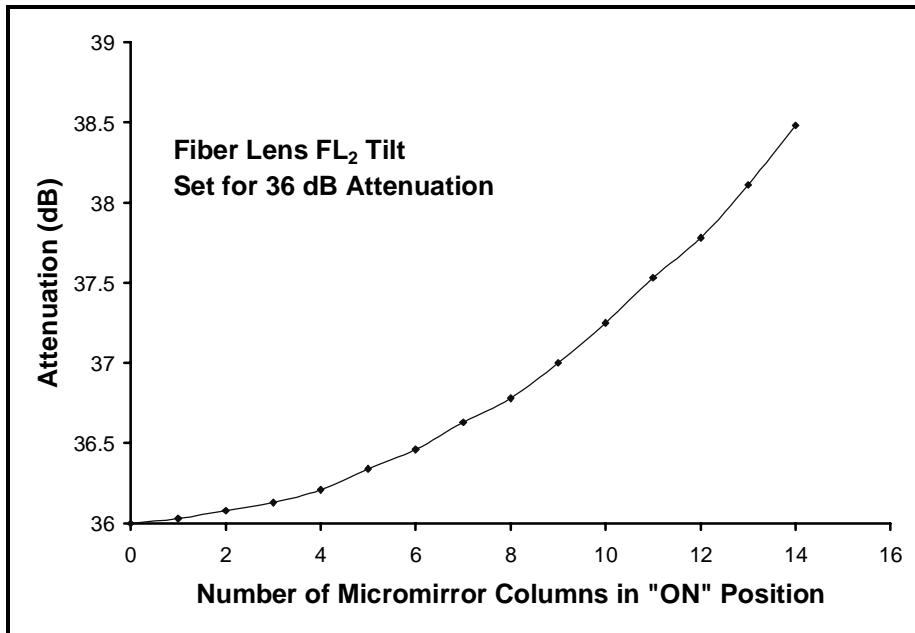
**Fig. 1:** Proposed Hybrid Design Analog-Digital MEMS VOA. FL: Self-Imaging Fiber Lens. SMF: Single-Mode Fiber, DMD<sup>TM</sup>: Digital Micro-mirror Device.



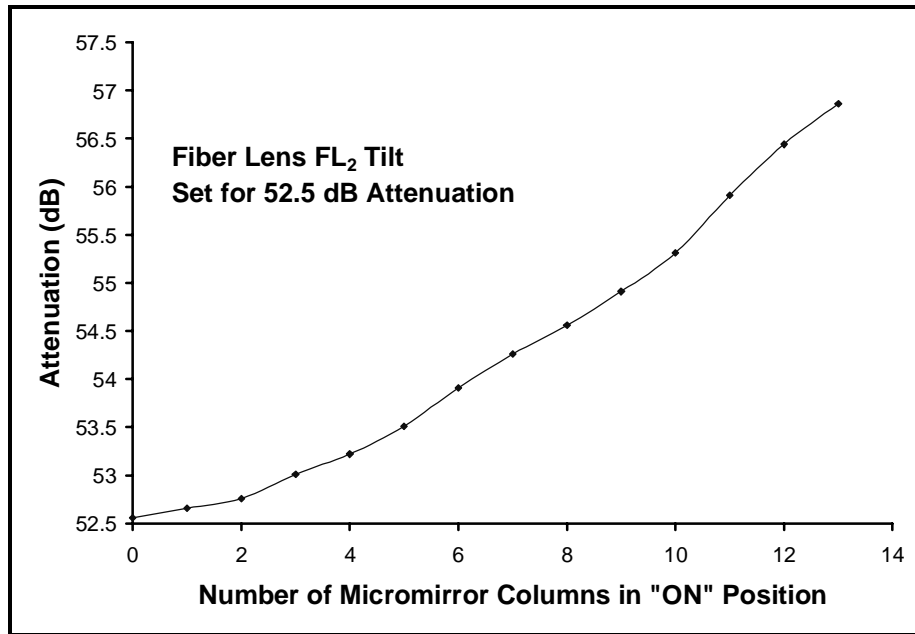
**Fig. 2:** Measured high 53 dB dynamic range attenuation produced by the proposed Hybrid VOA using up-to 0.23° tilt-only motion of the fiber lens FL<sub>2</sub>.



(a)

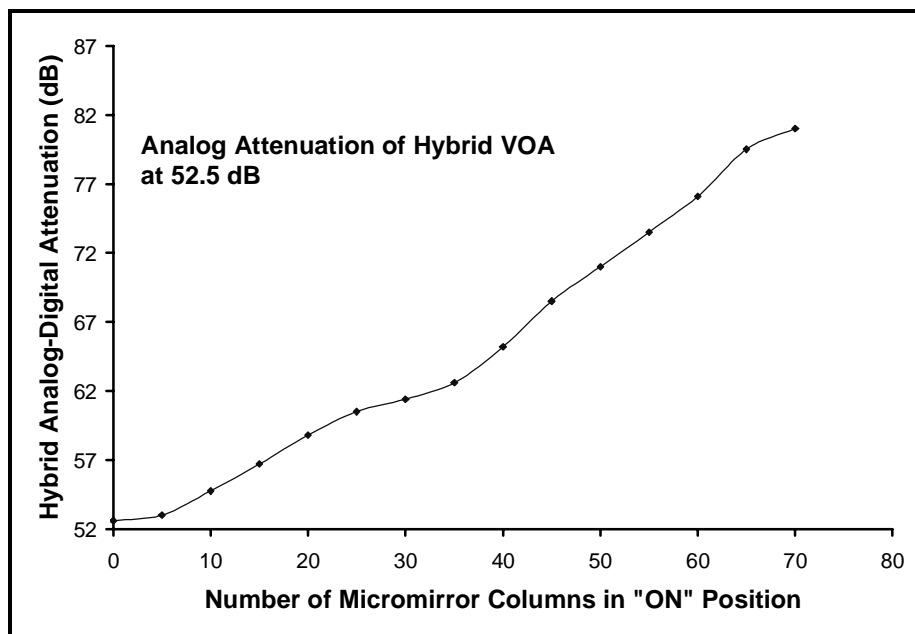


(b)



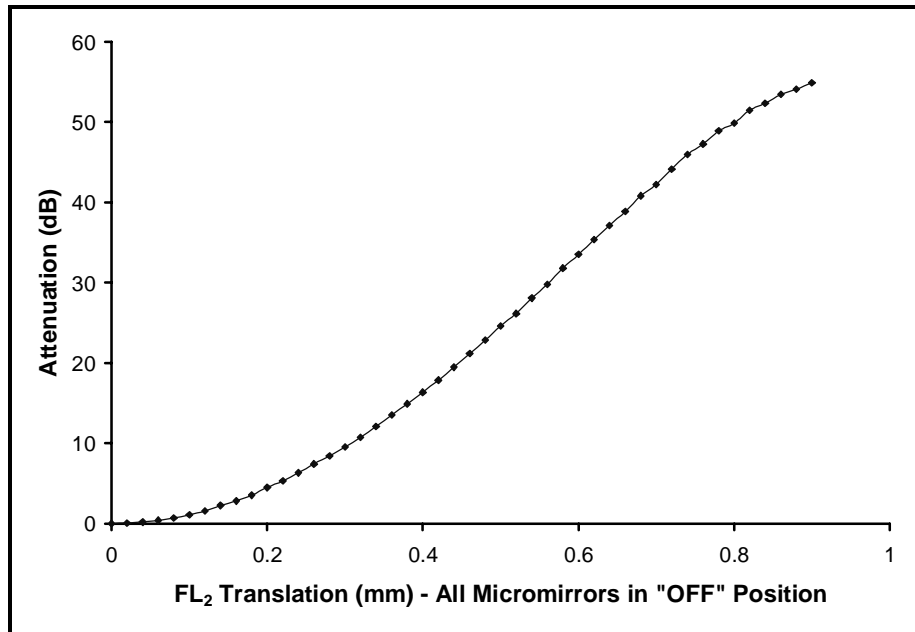
(c)

**Fig. 3:** Example measured digital attenuation control produced via pure digital micro-mirror 14 column control of the proposed Hybrid VOA when once set to a given attenuation setting via pure analog tilt control of fiber lens FL<sub>2</sub>. (a) The analog setting of the VOA is at 3.5 dB attenuation with an additional 0.88 dB produced by digital control. (b) The analog setting of the VOA is at 36 dB attenuation with an additional 2.48 dB produced by digital control. (c) The analog setting of the VOA is at 52.5 dB attenuation with an additional 4.36 dB produced by digital control.



**Fig. 4:** Measured hybrid analog-digital attenuation control produced via analog attenuation of 52.5 dB and 70 digital micromirror column control of the DMD™. The combined attenuation of the hybrid VOA gives an extremely high dynamic range of 81 dB.





**Fig. 5:** Measured high 60 dB dynamic range attenuation produced by the proposed Hybrid VOA using 1 mm translation only motion of the fiber lens FL<sub>2</sub>.