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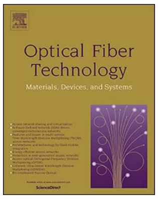

Regular Articles

A liquid lens switching-based motionless variable fiber-optic delay line

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ABSTRACT

We present a Variable Fiber-Optic Delay Line (VFODL) module capable of imparting long variable delays by switching an input optical/RF signal between Single Mode Fiber (SMF) patch cords of different lengths through a pair of Electronically Controlled Tunable Lenses (ECTLs) resulting in a polarization-independent operation. Depending on intended application, the lengths of the SMFs can be chosen accordingly to achieve the desired VFODL operation dynamic range. If so desired, the state of the input signal polarization can be preserved with the use of commercially available polarization-independent ECTLs along with polarization-maintaining SMFs (PM-SMFs), resulting in an output polarization that is identical to the input. An ECTL-based design also improves power consumption and repeatability. The delay switching mechanism is electronically-controlled, involves no bulk moving parts, and can be fully-automated. The VFODL module is compact due to the use of small optical components and SMFs that can be packaged compactly.

1. Introduction

VFODLs are crucial for providing tunable signal delay for applications in RF photonics [1], target ranging [2], medical imaging [3], phase-array beam steering [4] and photonic signal processing [5]. As opposed to short-delay VFODLs (with a few hundred pico-second range) which provide a tunable 2π phase scan to RF signals, long-delay VFODLs are capable of delaying the input signal by a few nano-seconds and useful for implementation of interferometric measurement systems and RF-Photonic tunable filters.

Various long-delay VFODL designs have been proposed in prior art. These include VFODLs that employ Nematic Liquid Crystals (NLCs) [6–7], digital Micro Electro-Mechanical Systems (MEMS) devices [8], Array Waveguide Gratings (AWGs) [9] and Acousto-optics [10] to switch the incoming optical signal between different fibers. Although most of these designs are motion-free but require bulky and expensive components thus limiting their potential use in commercial and research applications that require cheap and compact solutions. Even mid-performance NLCs and MEMS-based Spatial Light Modulators (SLMs) and AWGs cost at least a few thousands of dollars. Moreover, VFODLs ideally should be single input/single output devices for simplicity and ease of deployment into existing fiber-optic systems unlike [6–7] with no single common output port requiring to switch between input ports to alter the optical path of an incoming beam.

Similarly, the VFODL designs in [6–9] suffer from PMD for two linear orthogonal polarization states of input light. The drawback of using polarization-based dispersive components such as liquid crystals, PM-SMFs etc. is that the true delay incurred is polarization-dependent. For a truly PMD-free VFODL operation, two constituent orthogonal polarization components of input light must experience the same delay.

Other integrated and bulk VFODLs, proposed in prior art use simple diffraction gratings [11], Fiber Bragg Gratings (FBGs) [12] and fiber stretching [13] to achieve a variable signal delay. Some other designs based on tapered FBGs [14] and chirped FBGs [15] require the use of thermal and mechanical stress respectively to control the tuning properties of FBGs. These designs require either bulk motion of optical components or thermal stresses which degrades performance repeatability and reliability with use over time due to gradual mechanical wear-and-tear and introduction of optical defects [16–18]. In recent years, VFODL operation through the use of ECTLs has been demonstrated. A motion-based lossless free-space VFODL for long delays was proposed in [19] but it is slow and bulky as it requires motion of mirrors for lossless operation.

More recently, an ECTL-based motion-free VFODL was proposed in [20] which employs multiple ECTLs to impart an electronically-controlled variable free-space delay up to only a few pico-seconds. Besides providing a smart way to change propagation paths without significantly altering beam propagation properties between two fixed locations (which is how the VFODL in [20] achieved tunable delay operation), the work in [20] provides an additional insight into the possibility of laterally translating an input beam with a minimal or no angular shift through the use of ECTL pairs. This aspect of using ECTL

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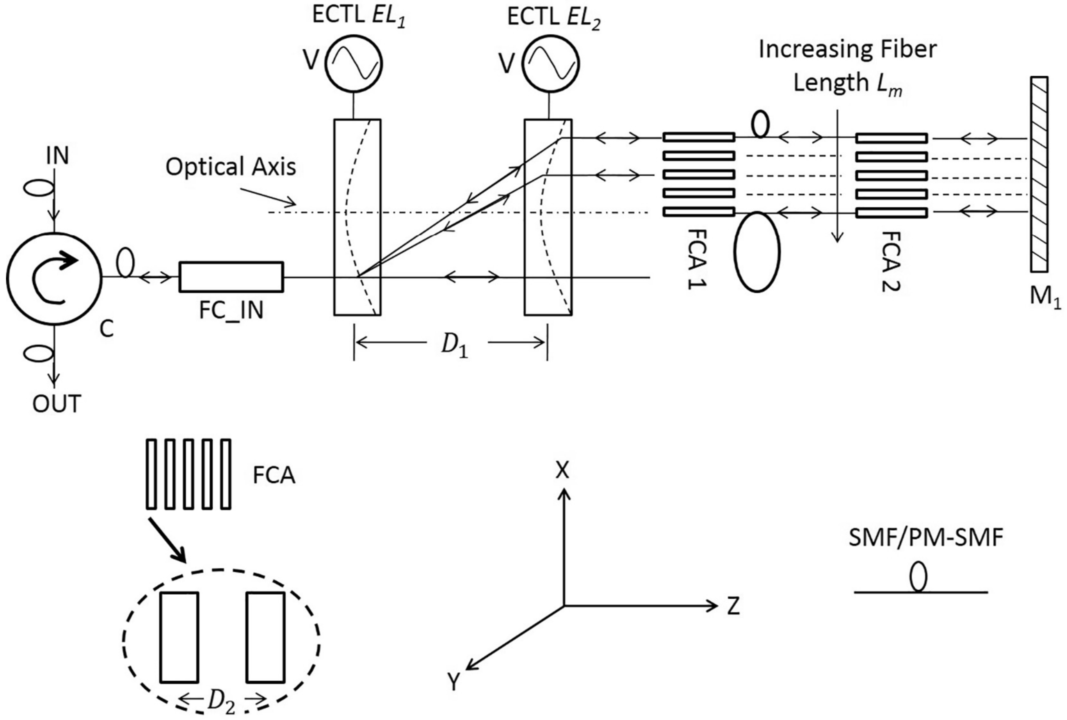

Fig. 1. Proposed VFODL using an ECTL pair (EL_1 and EL_2), an optical circulator C, collimator arrays FCA1 and FCA2, PM-SMFs and a mirror M_1.

pairs to translate a beam without introducing angular tilt in propagation path allows for the possibility of coupling different translated beam states into different equally-spaced elements of a linear Fiber Collimator/GRIN Array (FCA) like the one in [21]. Hence unlike beam path restoration in [20], in this paper the principal to achieve a variable delay is the ability of ECTL pair(s) to purely translate a beam laterally and coupling into any linear FCA with each element connected to a fiber patch cord of a different length. The proposed single input/single output VFODL design is compact, fully-automated and provides long signal delays.

2. Design of the proposed long delay VFODL

We present the proposed polarization-independent VFODL module in Fig. 1. The VFODL operation is based on laterally shifting an incoming beam by electronically controlling a pair of ECTLs and depending on the shift, coupling the shifted beam into SMF/PM-SMF patch cords of different lengths which are connected to a fixed linear FCAs. By electronically selecting the SMF optical path length, we effectively switch the input signal between different delay states.

Incoming light enters the system through the input VFODL port which is the IN port of an optical circulator C. The beam exits into free-space through circulator port 2 which is connected to a Fiber Collimator FC_IN. The free-space Gaussian Beam then passes through ECTLs EL_1 and EL_2 separated by a distance D_1. The beam is normally incident at EL_1 at an off-optical axis location that is h_1 below the optical axis of the two-lens system. After passing through EL_1 and EL_2, the beam exiting EL_2 is laterally displaced to a height h_2 above the optical axis and still propagates parallel to the optical axis only if the focal lengths f_1 and f_2 of EL_1 and EL_2 satisfy the condition:

$$D_1 = f_1 + f_2 \tag{1}$$

For the design in Fig. 1, depending on the ECTL focal length settings f_1 and f_2, the resulting total lateral displacement $D_{Lat} = h_1 + h_2$ couples the beam into one FC/GRIN lens within a linear array FCA1 of GRIN/FC elements. Knowing that $h_2/h_1 = f_2/f_1$, this displacement can be calculated in terms of h_1 and the settings of f_1 and f_2 (with f_1 and f_2 satisfying Eq. (1)) as:

$$D_{Lat} = h_1(1 + f_2/f_1) \tag{2}$$

Each GRIN/FC element in FCA1 is connected to an element of an identical FC/GRIN linear array FCA2 through an SMF fiber patch cord of a unique Optical Path Length (OPL) L_m which determines the total delay to the input signal. Here the subscript m denotes the mth SMF connecting the mth elements of FCA1/FCA2. The beam exits the SMF through FCA2, reflects back from a plane mirror M_1 coupling again into the same FC/FRIN element of FCA2. The backward propagating beam retraces its path through the VFODL module and exits via port 3 of the optical circulator. For compactness and low-loss operation, we can terminate each individual SMF patch into fiber mirrors instead of using FCA2 and a bulk mirror M_1. Also, for a completely free-space operation, a simple BS can be used instead of a C in order to isolate the input and output beams.

If a polarization-maintaining operation is desired, then we can use a linearly polarized input beam and use PM-SMF patches instead of simple SMFs. In this case the linear polarization of the input beam is aligned to one of the common primary principle polarization axes of the PM-SMF patch cords. The use of linearly-polarized input which is carefully aligned to one of the PM-SMF principle axes ensures that the reflected beam from M_1 (or fiber mirrors if deployed) has the same polarization as the input beam.

Satisfying the condition in Eq. (1) is critical in switching of polarization states by the use of an ECTL pair. The Optical Path Length OPL_{VFODL} is given by:

$$OPL_{VFODL} = n_S D_S + 2n_o L_m \tag{3}$$

here n_{air} is the refractive index of air and D_{air} is the total distance traveled in air after the beam exits FC_IN and recouples back into it. Also n_o is the effective refractive index experienced by the light passing through the SMF cord. The lengths L_m of PM-SMFs can be increased in equal steps ΔL for $m \geq 1$, i.e., L_1 is the PM-SMF length connected to the first collimator of the FCA. Therefore

$$L_m = L_1 + m\Delta L. \tag{4}$$

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