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Agile Optical Beam Scanners Using Wavelength and Space Manipulations

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ABSTRACT

An agile optical scanning scheme is proposed that uses wavelength manipulations for deflecting a free-space optical beam by selection of the wavelength of the light incident on a wavelength dispersive optical element. Using fast tunable lasers or optical filters, this scanner features microsecond domain scan setting speeds, single/multiple beam(s) in space, and large several centimeters or more diameter apertures for sub-degree angular scans. The beam scanning scheme offers simple control (via wavelength tuning). The paper also introduces space multiplexing for optical beam scanning and discusses various system architectures utilizing both space and wavelength multiplexing to achieve high speed optical scanning with coarse and fine tuning capability. Experiments described demonstrate high-speed, high resolution, wavelength tuned optical scanning in one-dimension (1-D), two-dimensions (2-D), and three-dimensions (3-D).

1. INTRODUCTION

Optical scanners are critical building blocks in numerous optical applications such as optical switching, laser ultrasonics, airborne and spaceborne studies of the geosphere, laser imaging for non-surgical biopsies, infrared countermeasures (IRCM), and laser communications. Applications such as laser communications and target designation presently require substantial improvements in laser beam steering technology. Optical scanners proposed so far rely on the use of one or more moving optical components such as mirrors and polygons in combination with electronically controlled inertialess optical devices. They include acousto-optic[1] (AO) scanners, electro-optic scanners using liquid crystals[2] and piezoceramic[3] devices, optical microelectromechanical systems (MEMS)[4] based scanners, and motion based microlens array scanners.[5] These scanners are performance limited because of high voltage requirements, small aperture sizes, small angular scan ranges, and/or inherent mechanical inertia. There is, therefore, a need to realize low power consumption, low cost, rapidly (e.g., a few μs or less) reconfigured laser beam scanners for steering, pointing and tracking. A new design technology called Multiplexed Optical Scanner Technology (MOST) was introduced[6] for laser beam steering which promises low power consumption and true rapid three dimensional (3-D) beamforming to accurately control beam position, power and shape. MOST exploits the various parameters of light such as time, space, frequency and polarization to deliver scanner designs that enable improved specific scanner performance parameters, for instance, enabling ultrafast scanner speeds. The Wavelength Multiplexed Optical Scanner (W-MOS) is a peer member of the MOST family. The scanner gets its power from high speed wavelength selection coupled with light interaction with a wavelength dispersive element that in turn leads to spatially dispersed beam scanning. There are two key versions of the W-MOS; namely, the free-space W-MOS and the fiber-remoted W-MOS. The fiber-remoted version can provide a scanner field of view (FOV) as large as 360^o and gives the powerful ability to scan large volumes and complicated 3-D geometries.[7] Recently, we have completed the theoretical analysis of free-space W-MOS [8] and have shown that the scanner can offer high resolution (e.g., $< 0.01^o$ for a 2 cm diffraction limited aperture diameter) large angular scans (e.g., $\sim 15^o$), all at sub-microsecond speeds, and proves an optimum choice for an efficient free-space lasercom system. The potential speed of this scanner can be in GHz using the present-day state-of-the-art nanosecond tuning speed lasers.[9] The free-space W-MOS has other important applications such as a high speed probe for dynamic

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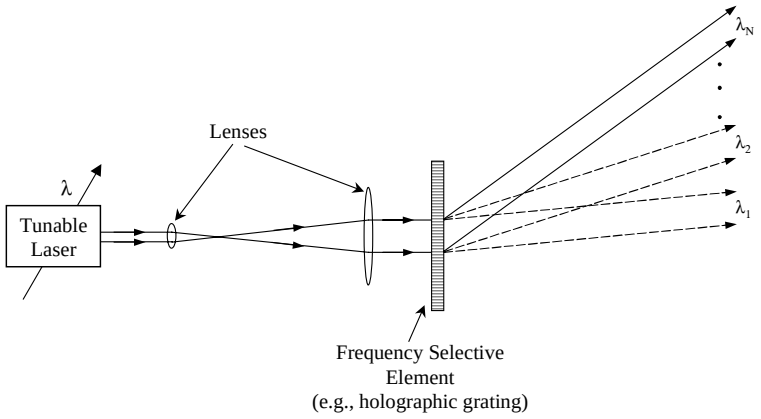
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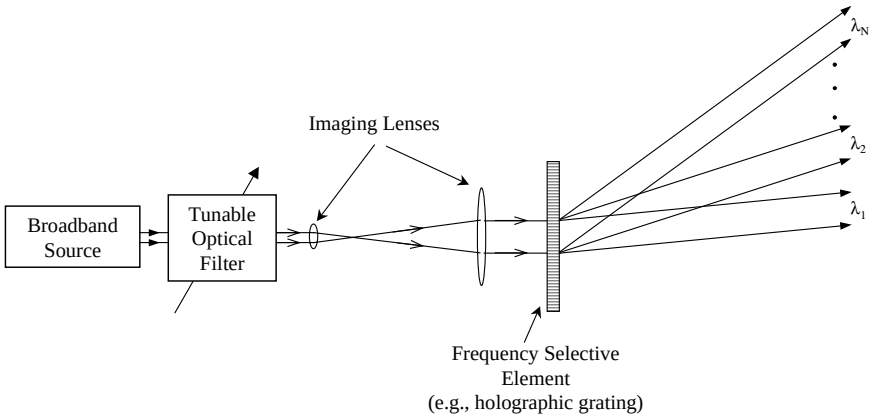
blood analysis,[10] optical data handling,[11] and agile high-speed optical interconnects.[12] The rest of the paper describes the free-space W-MOS designs with single and multiple scanning beams. The paper discusses the design and implementation of a fiber-remoted W-MOS. Experiments described demonstrate high-speed, high resolution, wavelength tuned optical scanning in one-dimension (1-D), two-dimensions (2-D), and three-dimensions (3-D). The paper also introduces space multiplexing for optical beam scanning and discusses various system architectures to achieve high speed optical scanning using components with no moving parts.

2. FREE-SPACE W-MOS DESIGN

This section discusses two versions of the basic structure of the free-space W-MOS. Fig. 1(a) shows the design with single beam high-speed 1-D scanning capability where the wavelength selection is achieved by tuning a laser. On the other hand, Fig. 1(b) shows the design with multiple beam high-speed 1-D scanning capability where beam scanning is achieved by selection of wavelength via a tunable optical filter such as an acousto-optic tunable filter (AOTF). In both cases, very high-speed beam scanning can be achieved using electronically tuned solid state lasers[13, 14] and filters[15, 16] with sub-microsecond response time. As Fig. 1 shows, the free-space W-MOS draws its power from its simple optical design and single drive beam control mechanisms. Specifically, the in-line laser with a collimated laser beam allows for beam expansion before striking the wavelength dispersive element such as a diffraction grating etched on a thin planar piece of optics. This in-turn allows the scanner to have large (e.g., several cms) diameter aperture leading to high angular resolution scans. If multiple wavelengths are used simultaneously, then multiple simultaneous optical beams in space can be generated by the W-MOS.



(a)



(b)

Fig. 1 Free-space version of the W-MOS for implementing no moving parts high speed one dimensional (1-D) scans using (a) a tunable laser and (b) a tunable optical filter cascaded with a broadband source.

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Another feature of the free-space W-MOS due to its free-space light paths is that light of linear polarization can be used to built the scanner, thus enabling the use of high performance polarization-based optical components, e.g., AOTF. In short, the free-space W-MOS offers powerful scanner features in a compact and simple to build and control package leading to potentially wide spread use of this technology.

3. EXPERIMENTAL VERIFICATION OF FREE-SPACE W-MOS

A proof-of-concept W-MOS system was setup in the laboratory to study the angular scan as a function of incidence angle θ_{inc} and the wavelength of the tunable source used. The W-MOS system was experimentally confirmed using a one-dimensional (1-D) blazed reflection phase grating (grating period L = 1/600 mm) as a dispersive element. The incident light on the grating came from a fiber-coupled, mechanically tunable laser with an 80 nm tunable bandwidth centered at 1560 nm. Light from the laser source was coupled into a single-mode fiber (9/125 μm) and collimated by a gradient index (GRIN) rod lens, as shown in Fig. 2. The angle of incidence θ_{inc} of the light was controlled by the rotational stage upon which the grating was attached. An infrared (IR) camera was used to observe the scanning +1 diffraction order when the wavelength of the tunable laser was changed. The angular deflection was measured by tracking the scanning +1 diffraction order with the help of an iris mounted on an aluminum C-channel with one end attached to a rotational stage having the same axis of rotation as that of the reflection grating.

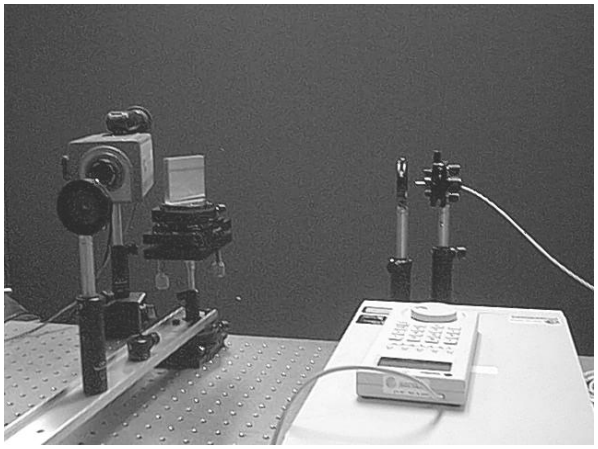


Fig. 2 Experimental setup to validate the theoretical angular scans obtainable from free-space W-MOS.

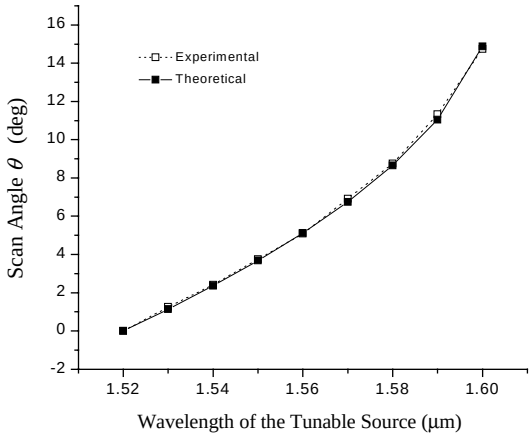


Fig. 3 Plot of the scan angle vs. wavelength for our free-space W-MOS ($\theta_{inc} = 2.2^{o}$).

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With its own rotational stage, the c-channel can be moved independently of the grating, and diffraction angles can be easily measured. The initial measurements were taken to determine how the grating behaved when compared to theoretical predictions of diffraction angles. The first setup involved positioning the grating such that $\theta_{inc} = 2.2^o$. At this angle of incidence, we expected to see a total scan range of 14.87^o. In the lab, we experimentally achieved a total scan range of 14.75^o, which is in complete agreement with the estimated angular scan. Fig. 2 shows the scan angle as a function of wavelength of the tunable source for $\theta_{inc} = 2.2^o$. It can also be observed from Fig. 3 that the experimental angular scan behavior (for the +1diffraction order) versus wavelength of the tunable source is in complete agreement with the theoretical scan behavior.

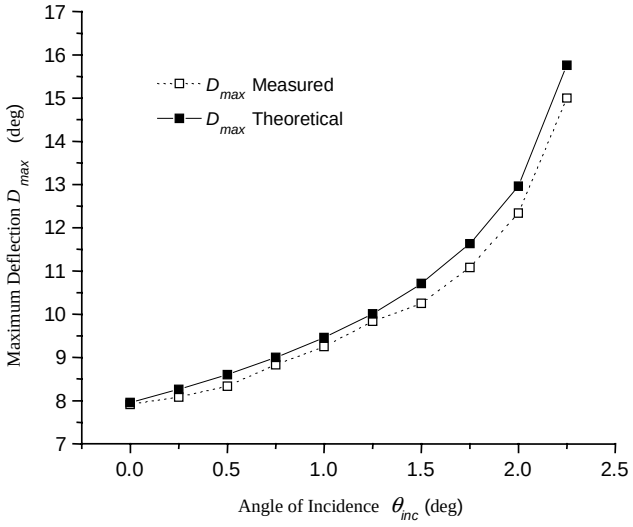


Fig. 4 Total angular scan D_{max} versus the angle of incidence θ_{inc}.

Another data set was collected with an intention to compare the theoretical and experimental values of total angular scan offered by the lab experimental W-MOS setup for different values of θ_{inc} between 0^o and 2.25^o. The results of these measurements are shown in Fig. 4. For each angle of incidence, the measured value of total angular scan was consistent with the theory. This study confirms that total achievable angular scan can be increased by adjusting the angle of incidence.

4. FIBER-REMOTED W-MOS DESIGN

This novel multi-dimensional optical scanning technique is based on fiber-based wavelength division multiplexed (WDM) technology. The scanner can provide large fields of view (e.g., up to 360^o), large scanning volumes, fast scanning speeds, and the ability to scan complicated three-dimensional (3-D) geometries. WDM devices have been recently used in telecommunication optical networks.[17] Commercial availability of very high density WDM devices with 128 or more channels at a 50 GHz spacing have become a reality.[18] In a 1:*N* WDM demultiplexer device, light in the input fiber channel containing *N* wavelengths is split into *N* independent fiber channels using an optical dispersion technique. Possible dispersive elements can include wavelength sensitive angularly multiplexed holograms, integrated-optic arrayed waveguide gratings (AWGs), bulk-optic interference-film filters, micro-machined Fabry-Perot filters, and fiber-Bragg grating devices. A variety of wavelength bands are possible, including the visible band using visible WDM devices.[19] Tuning the wavelength of the light beam input to the demultiplexer allows the light to come out from the appropriate fiber channel, and an optical scanner is realized.

The basic structure of our fiber-remoted W-MOS is shown in Fig. 5. In one design, a tunable laser is connected to a 1:*N* WDM device via a single mode fiber (SMF). The demultiplexer has *N* output channels, whose working wavelengths are λ_1, λ_2, ..., λ_N. Only laser beam of wavelength λ_i can pass through the i*th* fiber channel. These ports are further connected to *N* beamforming elements (BFEs). The BFE can be fixed such as a bulk lens, or a planar

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diffractive optical element (DOE) for beam shaping. The BFE can also be an optically or electrically programmable optical element, such as a liquid crystal beam steerer. For instance, a BFE can focus the beam on the surface of an object. On the other hand, it can scan small angles to interconnect the 3-D scan space. A significant advantage of this optical scanner is its flexibility as the scanning profile can be adjusted according to the configuration of the object. This scanner can realize one-dimensional (1-D), two-dimensional (2-D), and 3-D scanning by controlling the fiber port positions and the orientations of the BFEs. The speed of the scanner is based on the tuning speed of the tunable laser or wavelength selective filter. Recently a wavelength switching time of 25 ns has been reported in a sampled-grating DBR laser over a 44 nm bandwidth. Our scanner also provides simultaneous multiple beam generation capability via multi-λ drive. Using a circulator, a reflective architecture is also possible for the scanner.

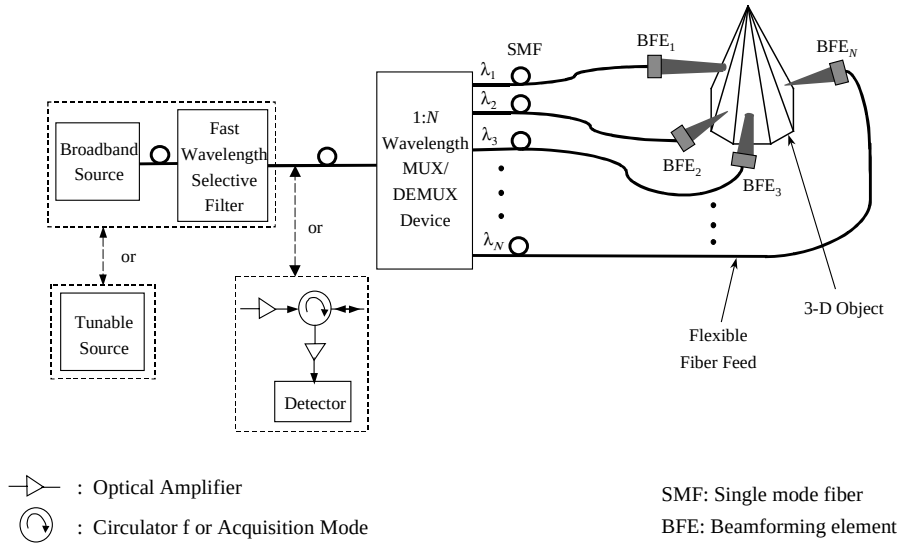


Fig. 5 Basic structure of our fiber-remoted W-MOS.

5. EXPERIMENTAL VERIFICATION OF FIBER-REMOTED W-MOS

An experimental setup for a 2-D and 3-D scan demonstration using our fiber-remoted W-MOS is shown in Fig. 6. A mechanically tuned fiber-coupled laser source with an 80 nm tunable bandwidth centered at 1560 nm was used as the tunable source. The wavelength sweeping speed of this mechanically tuned laser is limited to 170 ms/nm. The output of this tunable laser is coupled to a SMF that is connected to a 1:4 WDM demultiplexer at the other end. The output channels were connected to 4 GRIN lenses via FC/APC adapters. The working wavelengths of the four output channels of the demultiplexer were λ_1 = 1546.92 nm, λ_2 = 1548.52 nm, λ_3 = 1550.12 nm, and λ_4 = 1551.72 nm. The wavelength interval of two adjacent channels is 1.6 nm, which means that the minimum time interval in which the laser scans from one channel to another is 272 ms.

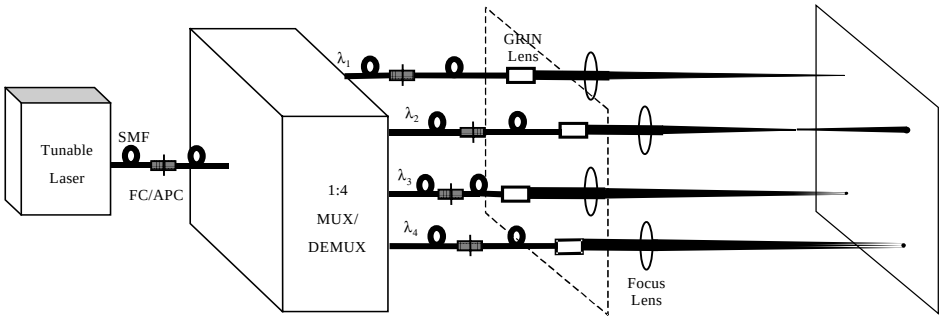


Fig. 6 Experimental setup of a 2-D and 3-D fiber-remoted W-MOS.

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Optical loss is defined as $10\times\log(P_{in}/P_{out})$, where P_{out} is the output optical power and P_{in} is the input optical power in the signal wavelength. The crosstalk parameter is defined as $10\times\log(P_{sig}/P_{\lambda})$, where P_{sig} is optical power in the signal wavelength and P_{λ} is the optical power in the other wavelengths. The scanner optical losses are 2.00 dB (λ_1), 2.81 dB (λ_2), 2.21 dB (λ_3), and 1.79 dB (λ_4), with an average loss of 2.20 dB. The crosstalk for the four channels were 33.29 dB (λ_1), 34.07 dB (λ_2), 32.68 dB (λ_3), and 36.74 dB (λ_4), with an average crosstalk of 34.2 dB. The loss is mainly due to the insertion loss of the demultiplexer and the two FC/APC adapters. In the 2-D scan test, no focus lens BFEs were used. For 3-D scan test, the focus lens BFEs focus beams at different positions so that a 3-D effect is realized. The scanning spots on the screen were recorded by an infrared camera connected to a video monitor. The spots from the different channels shown on the monitor are pictured in Fig. 3. The scanning spots are in good agreement with the output fiber pointing geometry.

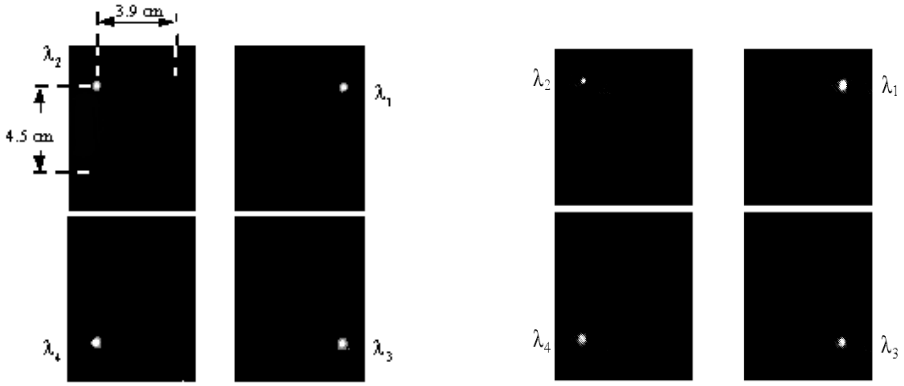
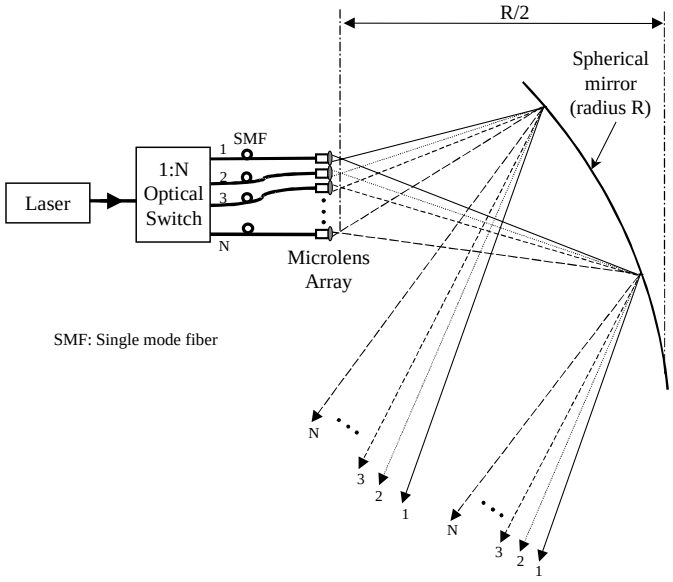


Fig. 7 Scanning spots at the monitor screen: (a) 2-D and (b) 3-D scanning cases.

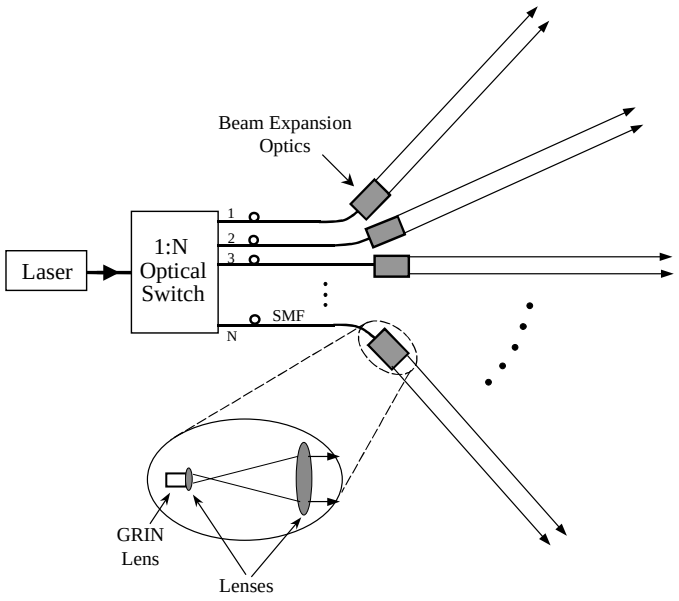
6. SPACE MULTIPLEXED OPTICAL SCANNER DESIGN

This section discusses space multiplexed optical scanner (S-MOS), another important member of the MOST family. Fig. 8 (a) and (b) show two versions of the basic structure of S-MOS. This scanner can be considered as a special case of the W-MOS.



(a)

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(b)

Fig. 8 Space multiplexed optical scanner: (a) Reflective topology using large mirrors (b) Transmissive topology using transmissive optics.

As shown in Fig. 8, the tunable laser has been replaced by a single wavelength laser connected to a 1×*N* optical space switch that further feeds a conformal fiber array. Fig. 8 (a) shows a reflective topology where the positions of the fiber/microlens output planes are designed to generate a 3-D beam control operation after reflection from a large mirror. Fig. 8 (b) shows a transmissive topology using refractive optics where the beam expansion optics array is distributed over a surface to generate a 3-D beam control operation. Each beam expansion optics consists of a GRIN lens and two spherical lenses. In each beam expansion optics, the collimated beam from the GRIN lens is focused and expanded by the first spherical lens whereas the second spherical lens again collimates the output expanded beam.

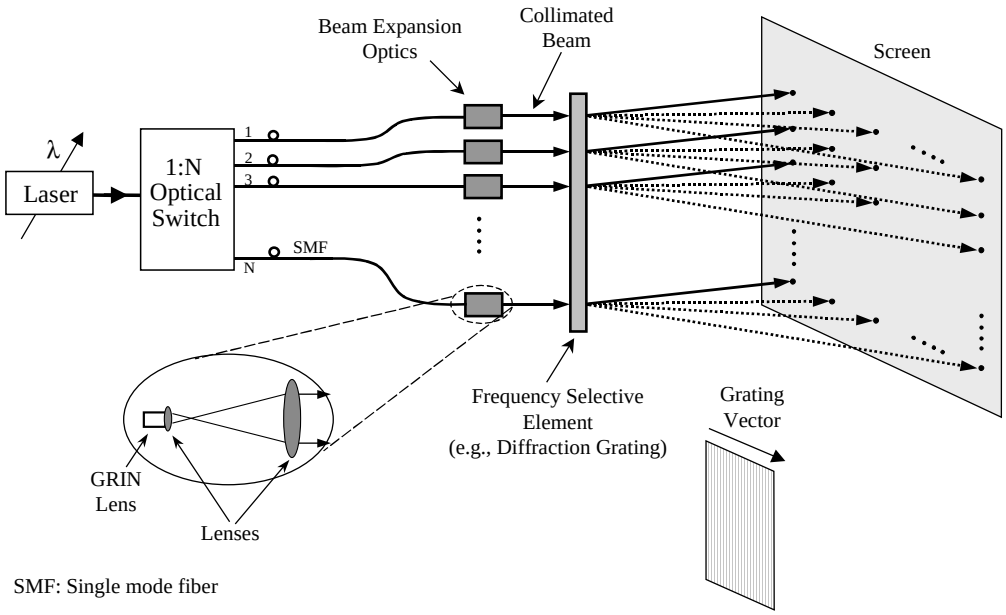
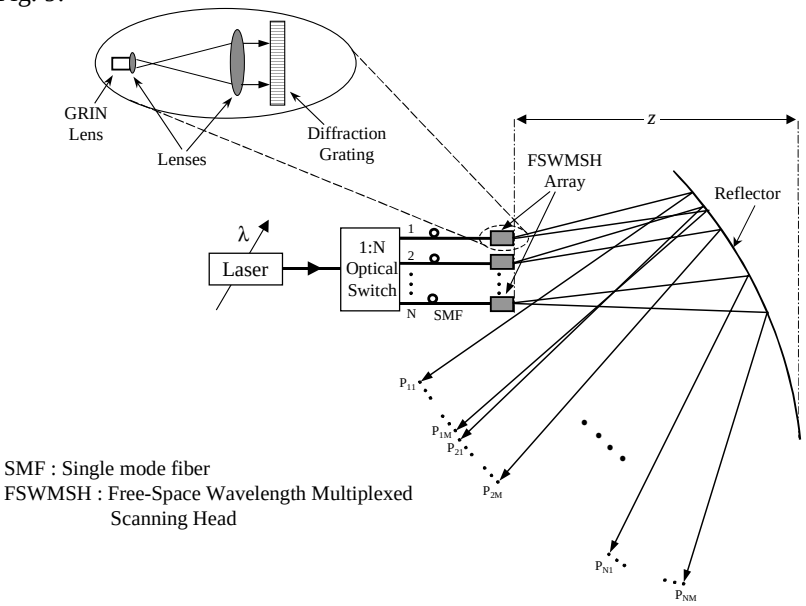


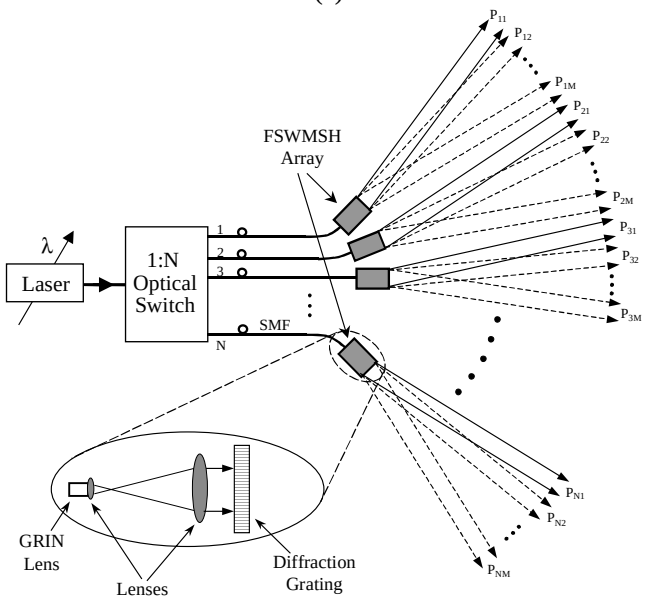
Fig. 9 A combination of S-MOS and free-space W-MOS to exploit raster scanning in 2-D.

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It is important to note that S-MOS does not require wavelength tuning, although tuning can also be exploited for security purposes as well as fine tuning of the scanning beams in 3-D. A combination of S-MOS and free-space W-MOS can be utilized to exploit raster scanning in 2-D, as shown in Fig. 9. The architecture utilizes a tunable laser source connected to a 1×*N* optical space switch that further feeds a conformal fiber array. Each fiber ends in a beam expansion optics module to expand the beam to required size. The beam expansion optics modules are arranged in a 1-D array in front of single beam dispersive element such as a diffraction grating etched on a planar piece of optics. It is important to note that the grating vector lies in a plane normal to the 1-D array of beam expansion optics modules. The laser beams exiting each beam expansion optics module are not necessarily normal to the grating. The angle of incidence can be adjusted for achieving optimum angular scan as discussed before. The scanning along the vertical direction is achieved by 1×*N* optical space switch settings. For each setting of the 1×*N* optical switch, the tunable source tunes the wavelength over the available bandwidth, which allows scanning in the horizontal direction. Thus a combination of an optical space switch and a tunable source in a synchronized manner allows raster scanning in 2-D, as shown in Fig. 9.



(a)



(b)

Fig. 10 A combination of S-MOS and free-space W-MOS to exploit 3-D coarse and fine beam control operation.

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As mentioned earlier, a combination of S-MOS and free-space W-MOS can be utilized to exploit a powerful beam scanning architecture with coarse and fine 3-D scan capability. Fig. 10 (a) and (b) show two novel 3-D beam scanning architectures utilizing a combination of S-MOS and free-space W-MOS. Each architecture uses a tunable laser connected to a $1\times N$ optical switch that further feeds a conformal fiber array. Each SMF ends in a free-space wavelength multiplexed scanning head (FSWMSH). The $1\times N$ optical switch provides coarse scanning in 3-D whereas the corresponding FSWMSH provides fine tuning of the scanning laser beam. The FSWMSH consists of beam expansion optics and a wavelength dispersive element such as a diffraction grating. Fig 10 (a) shows a reflective topology where the positions of the FSWMSHs are adjusted to generate a 3-D coarse and fine beam control operation after reflection from a large mirror. Fig. 10 (b), on the other hand, shows a transmissive topology using refractive optics where the FSWMSHs are distributed over a surface to generate a 3-D coarse and fine beam control operation.

7. CONCLUSION

In conclusion, we have proposed novel architectures for agile optical scanning. The free-space and fiber-remoted W-MOS use wavelength manipulations for deflecting a free-space optical beam by selection of the wavelength of the light incident on a wavelength dispersive optical element. Using fast tunable lasers or optical filters, free-space W-MOS features microsecond domain scan setting speeds, single/multiple beam(s) in space, and large several centimeters or more diameter apertures for sub-degree angular scans. On the other hand, a fiber-remoted W-MOS can provide large fields of view (e.g., up to 360^{o}), large scanning volumes, fast scanning speeds, and the ability to scan complicated three-dimensional (3-D) geometries. Both free-space and fiber-coupled wavelength multiplexed beam scanning schemes offer simple control (via wavelength tuning). Experimental results attest to the simplicity and functionality of our proposed novel schemes (using wavelength manipulations) for high-speed scanning. The potential speed of this fiber-optic scanning probe is in the GigaHertz rates using the present-day state-of-the-art nanosecond tuning speed lasers. Multiple beams can also be implemented in our W-MOS systems by using a broadband source (no tuning required). The paper also introduces space multiplexing for optical beam scanning and discusses various system architectures utilizing combinations of S-MOS and W-MOS to achieve high speed optical scanning in 2-D and 3-D with coarse and fine tuning capability. It is important to note that innovative grating designs can produce maximum angular scans with high diffraction efficiency. A grating with a short grating period and good diffraction efficiency in combination with a very high-speed tunable laser and an optical switch would allow W-MOS and S-MOS technology to satisfy the stringent specifications of modern military laser scanning technology.

ACKNOWLEDGMENT

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