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Fault Tolerant Photonics for Routing and Gain Controls

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ABSTRACT

SMP™: Spatially Multiplexed Processing technology is described that intelligently uses the spatial nature of light to form intelligent fiber-optic components and modules that provide fault-tolerance and improved optical signal setting speeds.

1. INTRODUCTION

Fundamental to both commercial and military communications is the capability to securely and robustly transmit and receive analog and digital signals. This security and fault-tolerance is required in critical military scenarios such as command and control operations where sensitive information is transferred to various nodes in a network or point-to-point link. This information robustness is also required in short scale signal distributions and controls such as phased array radars and electronic warfare systems.

The wide bandwidth of the optical fiber makes it the preferred channel for signaling in commercial and military systems. Wavelength division multiplexing (WDM) technology now dominant in commercial digital communications can be useful in military scenarios. Specifically, the use of multiple wavelengths in a system or network adds inherent redundancy and fault-tolerance to otherwise single wavelength systems/networks that have catastrophic failure. Today, military signaling systems are generally lacking in their use of WDM technology.

The service provider require the following features from its fiber-optic-based signaling systems and networks, namely, fault-tolerance and redundancy on both a device and system level, fast reconfigurability, temperature robustness, and dual robust Analog/Digital signaling operations. Today, microelectromechanical systems (MEMS) micromirror chip device technology has shown the capability to realize the goals of temperature robustness and moderate speed (e.g., milliseconds) reconfigurability, with the other service provider goals still allusive.

It was recognized in the early 1990s by GE [1] and TI [2] groups that MEMS-based optics could be used to form temperature robust variable optical delay lines for military phased array radar applications. Today, MEMS has evolved into a dominant technology for building WDM components.

Today, all analog operation components such as variable optical attenuators (VOAs), tunable filters, tunable lasers, and gain equalizers are built using analog MEMS technology where a micromirror is tilted/translated in an analog/smooth fashion, hence requiring expensive and sensitive feedback circuitry. Interference/diffractive MEMS concepts for beam control have also been introduced that uses a very large number of small micromirrors in a piston like fashion to form a diffractive beam steering element. This concept is interference based and requires precise sub-micron control of hundreds if not thousand of micron-scale mirrors adding to the complexity of the control electronics. On the signal routing side, today's MEMS-based all-optical switching solutions for all digital functions such as add-drop filtering and crossconnects rely on MEMS that is intrinsically susceptible to single point failure as these devices use one micromirror per beam.

The proposed SMP™ MEMS technology solves the mentioned problems, providing fault-tolerance and feedback control-loop free robustness. For example, SMP™ MEMS technology can use a few (< 20) small tilt micromirrors that are deployed in a non-interference based geometrical optics regime where unwanted loss and crosstalk diffraction effects are negligible, leading to a robust digital all-optical component or module.

WDM and Photonic Switching Devices for Network Applications III, Ray T. Chen,
Joseph C. Chon, Editors, Proceedings of SPIE Vol. 4653 (2002) © 2002 SPIE · 0277-786X/02/$15.00

2. NUONICS SMP™ TECHNOLOGY

Nuonics has proposed a paradigm shift from how one has previously built fiber-optic WDM components using MEMS or any other pixelated spatial modulation device technology. Specifically, a " Digital Spatial " paradigm has been proposed that forces each individual optical beam to interact with an array of independently controlled digital-mode micromirrors called a "Macro-pixel." Nuonics calls this patented [3] design approach " Spatially Multiplexed Processing" or SMP™ technology that forms the basis of several key optical modules and components that are required in commercial and military systems. For instance, SMP™ MEMS can be used to form variable attenuators, WDM equalizers, tunable filters, tunable lasers, data encoders, 1x2/1xN/NxN switches, and WDM reconfigurable add-drop (A-D) switches. The proposed SMP™ MEMS technology for the first time simultaneously brings in the following innovative features to the world of fiber-optics.

- Fault-tolerant Design: MEMS is a moving parts technology and hence reliability is a key concern. Because in SMP™ an optical beam is controlled by N micromirrors (e.g., N=10) instead of one micromirror, the reliability is essentially improved by a factor of N. Hence, single point fiber-optic catastrophic failure is avoided. Each micromirror can involve at most 3-D motions, i.e, two tilts and one translation. Any single or combination motion can be deployed to enable the desired beamforming.
- Digital Robustness: All micromirrors in the MEMS chip operate in a binary two tilt-state digital mode giving it all the benefits of digital operations such as excellent repeatability, ease in controls via digital interface electronics, and software upgrading of macro-pixel modes.
- Robust Analog Operations via Digital Modes: Highly repeatable analog optical beam attenuation controls is possible by controlling the "on" and "off" states and sizes of the individual micromirrors in the macro-pixel. Hence, both digital and analog operations are possible via robust digital controls.
- Faster Reconfigurations: Because each beam uses smaller micromirrors versus one large micromirror and the mirrors operate in small tilt modes (a few degrees), the response time of these devices can approach the tens of microseconds regime. This is unlike presentday single large mirror MEMS with typical millisecond speeds. Also, there is no alignment versus speed tradeoff as the optical beam can still be large as the macropixel is large, but the individual mirrors are small to give fast speed.

3. THE RATIONALE

Advanced commercial and military signal processing systems and communications networks can benefit from the wide bandwidth signaling capabilities of the optical fiber. Furthermore, the next natural step is to deploy WDM technology in DOD fiber-optic scenarios. The first benefit of WDM is the use of multiple wavelengths that lends itself to redundancy and fault-tolerance in the network architecture. In otherwords, instead of using a single well defined wavelength system, multiple wavelengths can be manipulated to securely transmit information. The next evolution in point-to-point WDM is to use intelligent wavelength allocation and routing to form smart and secure WDM-based military networks such as a distributed sensor network or a secure optically coded communications channel. In order to achieve these signaling system and network goals, a new class of fault-tolerant fiber-optics is required that are not prone to catastrophic device-level failure.

Today MEMS forms an ideal temperature robust device platform for realizing WDM fiber-optics. Nevertheless, MEMS is still a moving parts device and todays optical MEMS for WDM uses a single micromirror to control a given wavelength or optical beam. Hence, if the micromirror malfunctions, the fiber-optic component or module suffers catastrophic failure. Hence, todays optical MEMS lacks fault-tolerance, a fundamental need for military scenarios. Furthermore, present-day optical MEMS implements all important analog signal processing operations such as variable attenuation controls, optical filtering, and wavelength tuning via fundamentally analog operations such as gradual translation of a micromirror. Hence, this smooth approach to micromirror control is highly sensitive to electronic drive and environmental conditions, making modules costly due to expensive feedback electronics. Hence presentday components suffer from limited repeatability and poor robustness. Speed is also an issue with present-day MEMS devices as in order to gain speed, the micromirrors are made smaller. This in-turn leads to higher sensitivity for alignment as beams have to hit a smaller target. Thus today exists a dilemma between speed and packaging sensitivity for optical MEMS devices.

In short, key limitations exists with how todays optical MEMS-based fiber-optics are designed, and a design paradigm change is required for next generation fiber-optics to become fault-tolerant, fast, simple to control, and robust/highly repeatable. Nuonics has invented this new paradigm for fiber-optic MEMS that will allow a new class of components and modules to be deployed in military systems and communication networks for robust signaling of analog/digital information.

4. SMP™ TECHNOLOGY-BASED FIBER-OPTICS

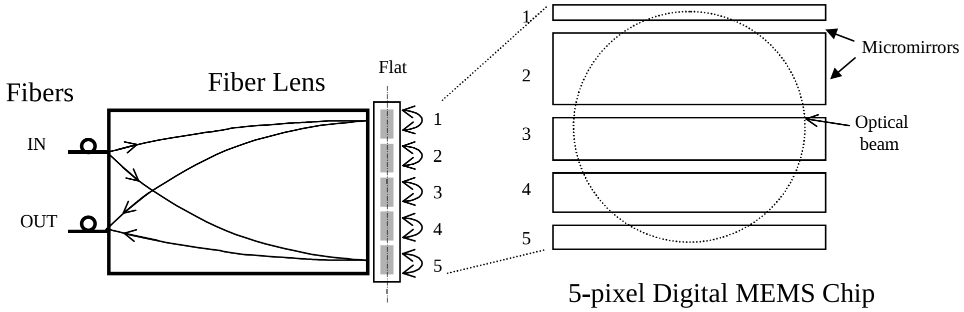

Fig.1: The proposed paradigm shifting fault-tolerant all-digital MEMS-based single channel variable optical attenuator (VOA) where both the device level MEMS chip and controls are digital even through the signaling operation is analog.

Fig.1 shows the simplist implementation of the proposed SMP™ MEMS technology to realize an analog optical signaling operation via pure digital means. The example uses a N=5 micromirror design that forms an N=5 bit VOA. The key design point to note is that the five mirror sizes and locations are specifically designed to implement a binary scaling in optical power to realize 2^N levels of power controls via N-pixel digital tilt/no-tilt controls. Another important point is that each micromirror has two states. One state is the flat state where light from the input fiber after passing via a fiber collimation lens travels right back to the output fiber. The other micromirror state is its tilt state where the micromirror tilts in excess of a few degrees, preventing light back into the output fiber. Thus by digitally controlling the tilt states of the N micromirrors, an all-digital N-bit VOA is formed, giving it all the powerful attributes of SMP™ MEMS technology.

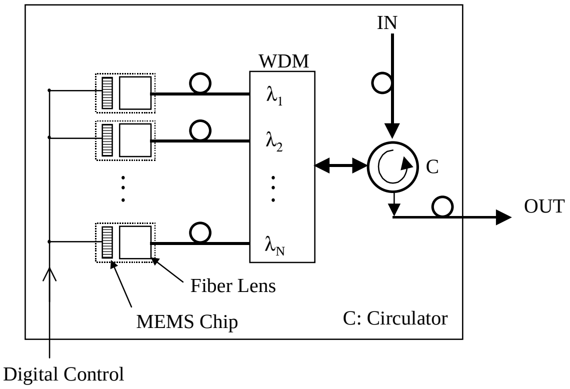

Fig.2: Shows how the same basic digital SMP™ MEMS technology concept in Fig.1 can be extended to form a digital WDM gain equalizer /tunable wavelength filter.

Fig.2 shows a block diagram of the proposed WDM gain equalizer /tunable wavelength filter using SMP™ MEMS technology. The key innovation is that an array of MEMS macro-pixels is required to implement the all-digital wavelength specific processing. Each macropixel can be on its specific MEMS chip, allowing ease of repair during chip malfunction. For a more compact chip scale (CS) arrangement, all macropixels are on a single MEMS chip. If pixels are operated in an N-bit variable mode, the module in Fig.2 forms a wavelength specific gain controller or equalizer. If all the micromirrors in each macro-pixel are jointly operated in either flat or tilt state modes, the Fig.2 module becomes a digitally controlled wavelength tunable filter. Further CS integration can integrate the WDM and circulator with the MEMS chip to form compact modules.

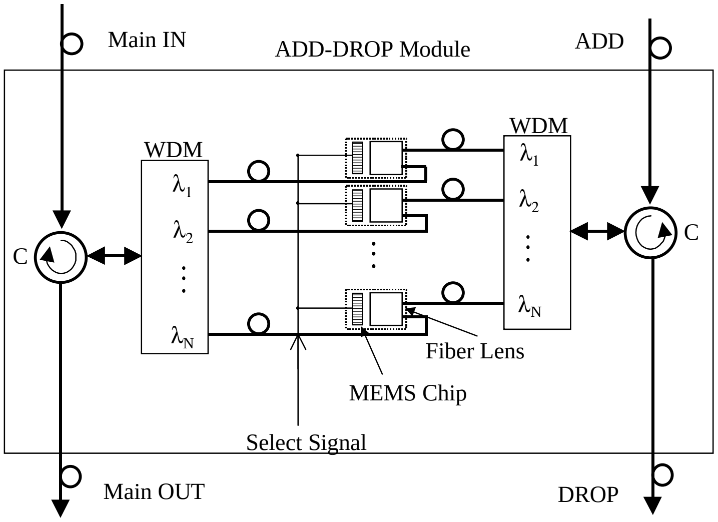

Fig.3: Shows how the same basic digital SMP™ MEMS technology concept in Fig.1 can be extended to form a WDM wavelength add-drop switch.

Fig.3 shows another proposed module called a WDM A-D switch that allows the simultaneous dropping and adding of selected wavelengths. The key innovation here is that the MEMS chip operates in a tilt mode and a retroreflective mode (versus the flat mode in the VOA). Hence, for main-in to main-out light flow, the MEMS chip retroreflective mode is used where light launched from the main-in port gets sent back via the same fiber at the MEMS chip. Hence a subtle play with our MEMS chip states allows formation of a new class of reconfigurable WDM component. Once again, various blocks in Fig.3 can be integrated.

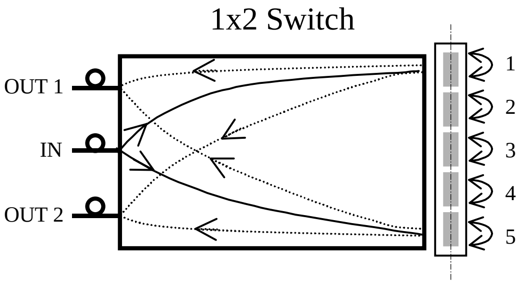

Fig.4: Shows how the same basic digital SMP™ MEMS technology concept in Fig.1 can be extended to form a compact 1x2 MEMS fault-tolerant switch.

Fig.4 shows how digital SMP™ MEMS technology can be used to form a robust 1x2 switch. Here again the micromirrors are operated together with either a flat state or a given tilt state. The sizes of all mirrors can be such as to bear equal power as this component operates as a switch. The 1x2 switch in Fig.4 forms a robust switching building block that can lead to a new generation of fault-tolerant 1xN and NxM MEMS-based switching modules.

Fig.5 shows how digital SMP™ MEMS can be incorporated into a laser cavity to form a tunable fiber laser. Once again, the power of repeatable digital operations is showcased.

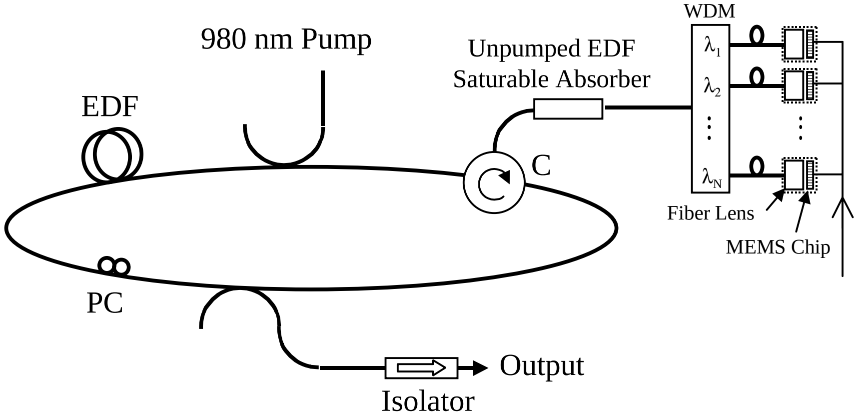

Fig.5: Shows how digital SMP™ MEMS technology can be used to form a robust digitally controlled tunable fiber laser.

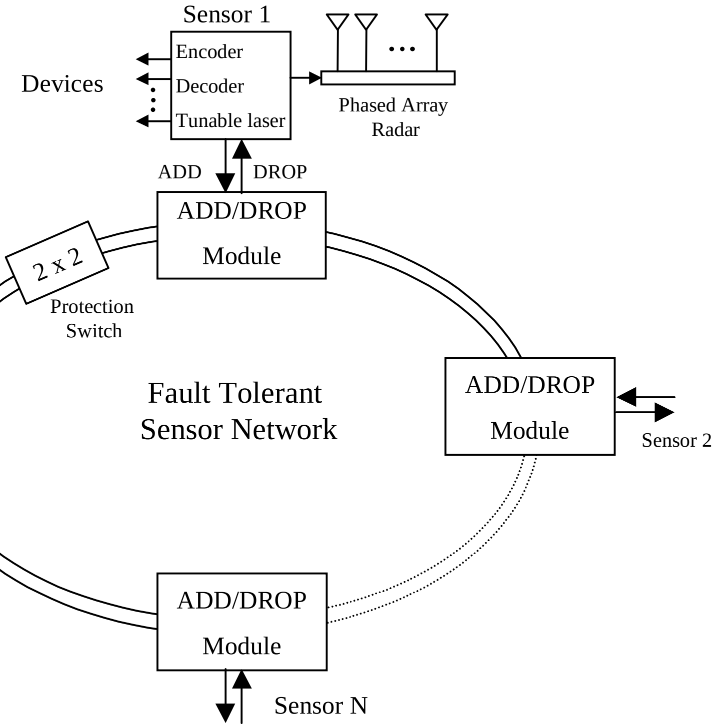

Fig.6: Shows how our proposed digital SMP™ MEMS technology-based components can be deployed in a distributed sensor network.

Fig.6 shows how WDM and digital SMP™ MEMS technology-based components can be exploited to realize a new class of fault-tolerant sensor network that is digitally robust both on a device and network level. The ring has fiber malfunction protection while the components are fault-tolerant and digitally robust on a device level.

Fig.7 shows a novel application of WDM and digital SMP™ MEMS technology-based components to form a secure communication link. Note that the encoder is based on the proposed WDM equalizer/ tunable filter. Here given analog/digital data D1, D2,..DN is mapped via a key code to N wavelengths. By controlling the MEMS chip, this data is

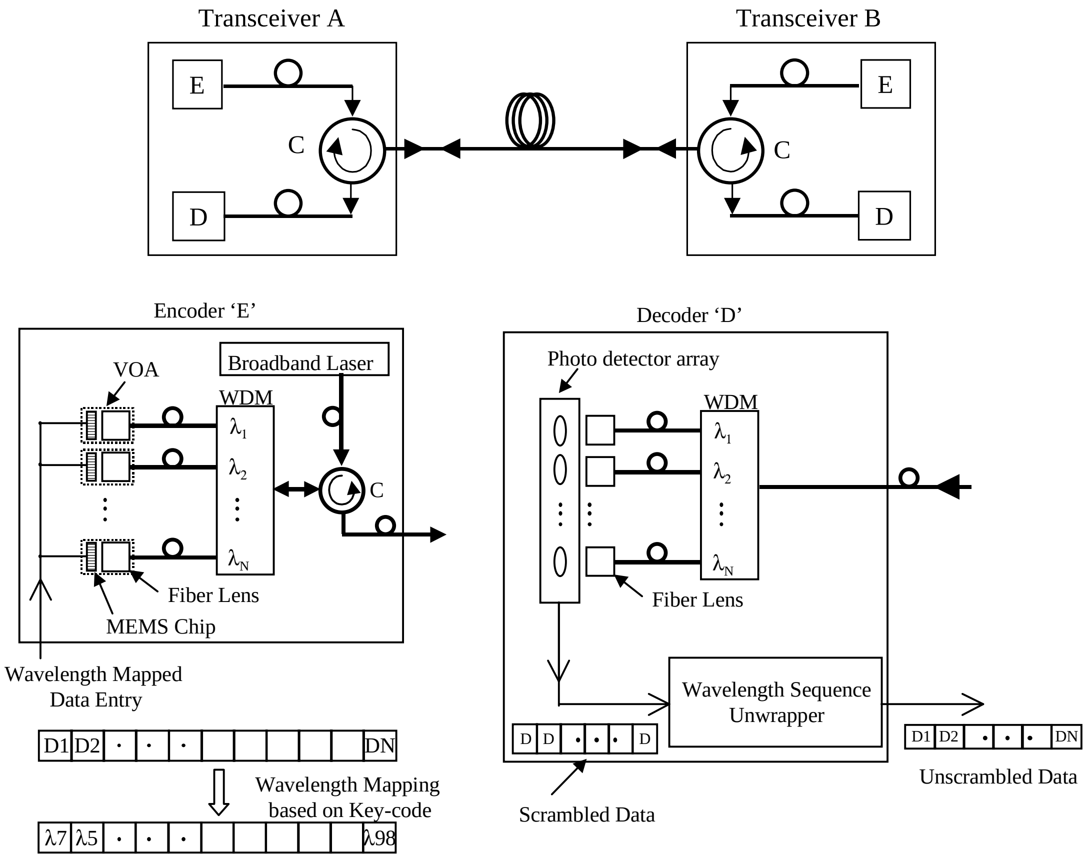

Fig.7: Shows another example of the use of WDM and digital SMP™ MEMS technology-based components that realize a new class of wavelength-mapped optically coded secure communications. E: Encoder; D: Decoder; C: Circulator.

encoded onto the optical beam for transmission. For decoding, a wavelength unwrapping key-code is used to decode the information via software. The data tranmission rate depends on the MEMS chip modulate rate multiplied by the number of wavelengths deployed in parallel. In a sense, this coding approach corresponds to spatial/image-based optical coding. After each transmission sequence, the key-code can be changed for added security. In conclusion, novel signaling scenarios are possible using the proposed using SMP™ MEMS technology-based components.

5. CONCLUSION

Earlier, we have successfully proven the concept of SMP™ MEMS technology using the commercially available TI digital micromirror device for visible light display applications [4]. This device has half a million micromirrors optimized for red, green, and blue light, and is not optimized for infrared SMP™ MEMS technology-based fiber-optics. A new class of SMP™ MEMS technology has been described that is suitable for fiber-optic applications. Furthermore, we have previously suggested the use of spatial codes and WDM for optically secure communications [5-6]. Here, we further develop these spatial coding concepts for a new class of secure optical links such as shown in Fig.9.

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