DLP™ Switched Blaze Grating; the Heart of Optical Signal Processing

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ABSTRACT

We have developed an approach for processing communication signals in the optical domain using a DLP™ digital mirror array driven by a Digital Signal Processor (DSP). In optical communication systems, modulation rates of 10 GB/s and above are common, hence, direct processing of Dense Wavelength Division Multiplexed (DWDM) optical signals without undergoing Optical to Electrical conversion has become a key requirement for cost effective deployment of dynamic optical networks. This work will discuss primarily applications of Optical Signal Processing (OSP) to coherent DWDM signals. Optical Signal Processing has also found applications in spectroscopy, microscopy, sensing, optical correlation, and testing.

1. INTRODUCTION

Our development of OSP is driven by the need for all optical signal processing in communication networks. There are a number of applications outside of optical communication networks but the current paper will highlight networking applications. Wavelength specific OSP functions include grooming, switching, add/drop/blocking and performance monitoring are needed for the optical network. Currently, these functions are performed almost entirely with static and single function devices or modules or via OEO conversion. As optical communications signals are modulated at 10 GHz or higher and are densely multiplexed, it has become prohibitively expensive to perform OEO conversions or to cascade optical modules performing these necessary signal-processing functions.

It is, in fact, at the higher modulation rates and dense multiplexing of wavelengths where direct optical signal processing becomes a requirement for optical networking. Optical signal processing at the optical layer enables dynamic and remote grooming and switching within the optical layer. Our approach uses field-proven devices produced in high volume, which add no power penalty and exhibits very low insertion loss. As will be described later, the very low insertion losses are obtained with micro-mirror arrays by matching diffractive effects with mirror tilt angle giving rise to a Switched Blazed Grating (SBG) device.

2. METHODOLOGY

In our embodiment shown in Figure 1, a SBG mirror array is used as a spatial light modulator capable of manipulating the amplitude, direction and phase of a light beam within the active area. A custom programmed Digital Signal Processor is used to communicate with the network via custom or standard interfaces and generates mirror patterns for the modulator based on received instructions. Also shown in Figure 1 is coprocessor (ASIC or FPGA), which accelerates the data load of the mirror array, and a SBG reset chip, which handles the reset signal used to cause mirror state changes. Very low insertion losses (~1.25 dB) of single mode signals over the DWDM band are obtained with the SBG modulator.

The SBG modulator is based on TI's DLP™ micro-mirror technology. Shown in Figure 2 is a top view of a 13x13 section of a mirror mosaic. A standard array format used in this application consists of 1024x768 individually addressable mirror pixels. Figure 3 is a cross-section of two mirror-pixels comprising a typical light modulator. The Switched Blazed Grating is of a class of modulators referred to as pixelated Spatial Light Modulators (SLMs). A pixelated spatial light modulator is comprised of a mosaic of discrete elements and can be constructed as a transmissive or reflective device. In the case of the SBG, the discrete pixel elements are micrometer size mirrors, and hence are operated in reflection. Each SBG consists of hundreds of thousands of tilting micro-mirrors each mounted to a hidden yoke. A torsion-hinge structure connects the yoke to support posts. The hinges permit reliable mirror rotation to nominally a +9 degree or –9 degree state. Since each mirror is mounted atop a SRAM cell, a voltage can be applied to either one of the address electrodes, creating an electro-static attraction causing the mirror to quickly rotate (15 microsecond transition time) until the landing tips make contact with the electrode layer. At this point the mirror is electro-

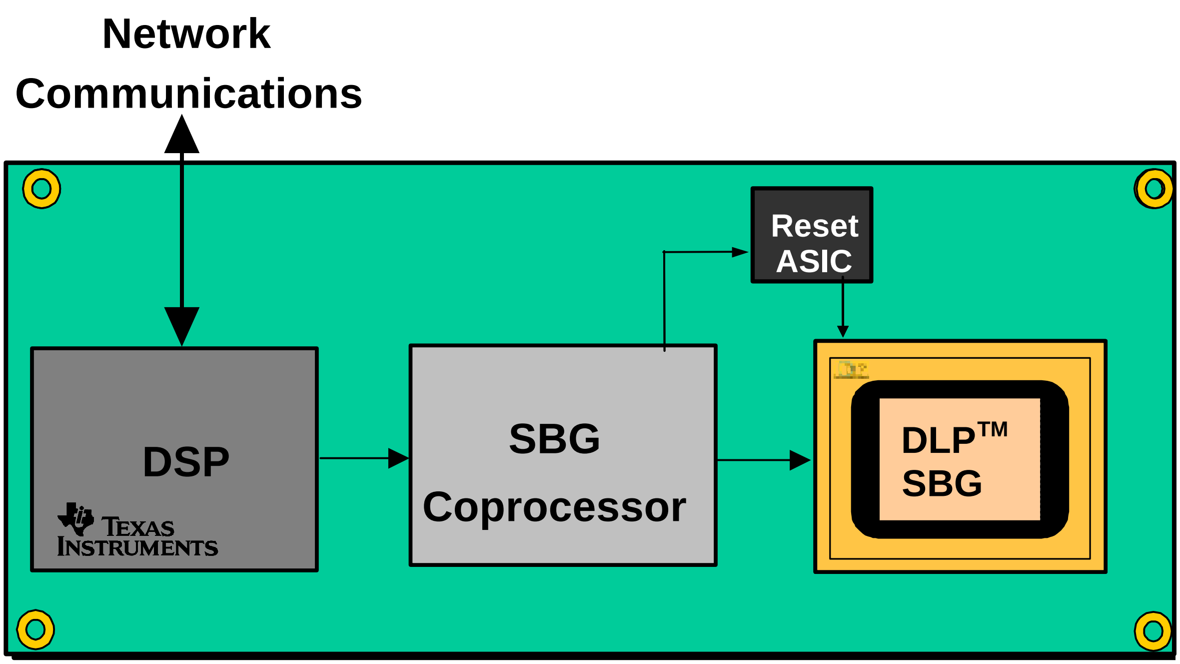

Figure 1. Block diagram of optical signal processor using a DLP™ SBG spatial light modulator together with a Texas Instruments Digital Signal Processor.

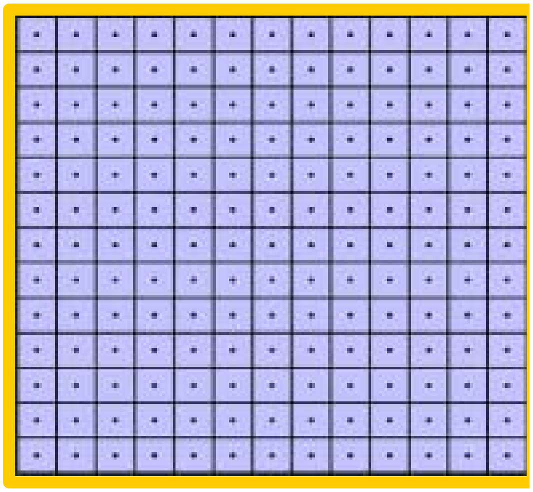

Figure 2. 13 x13 Mosaic of mirror pixels in unpowered state. DLP™ SBG light modulator consists of 1024x768 individually addressable mirror pixels.

mechanically "latched" in its desired position (see Figure 3). SBG are manufactured using standard semiconductor process flows. All metals used for the mirror and mirror substructures are also standard to semiconductor processing.

The total integrated reflectivity of a mirror array (i.e. reflectivity into all output angles or into a hemispherical solid angle) is a function of the area of the mirrors constituting the array, the angle of incidence and the reflectivity of the mirror material at a specific wavelength. (A consideration of second order effects on the integrated reflectivity would include weak effects such as light rays scattered from the mirror gaps.) To determine the power reflected into a small, well-defined, solid angle, one must know the pixel pitch or spacing in addition to the factors that control the integrated reflectivity (i.e. mirror area, angle of incidence and reflectivity). A pixelated reflector, the SBG behaves like a diffraction grating with the maximum power reflected (diffracted) in a direction θ_r, relative to the surface normal, determined by the pixel period, *d*, the wavelength, λ, and the angle of incidence, θ_i. Figure 4 depicts the optical layout in which the maxima in the reflectivity distribution function is governed by diffraction, $d(\sin\theta_r + \sin\theta_i) = n\,\lambda$, where n is the order of diffraction. The condition in which the direction of incidence and diffraction are identical ($\theta_i = \theta_r$) is referred to as the Littrow configuration, and the diffraction equation reduces to the well-known Bragg equation, $2d(\sin\theta) = n\lambda$. The tilt angle of the mirrors strongly controls the reflective power. The Fraunhofer diffraction in the Littrow case directs the light into a ray with an angle equal to the angle of incidence ($\theta_i = \theta_r$). When the angle of the Fraunhofer diffraction is equal to a diffractive order, the SBG is said to be blazed, and greater than 88% of the diffracted energy can be coupled into a single diffraction order (Figure 4 illustrates the blazed condition.). Using this blazed mirror approach, insertion losses of about 1.25 dB can be achieved for the SBG. The diffractive

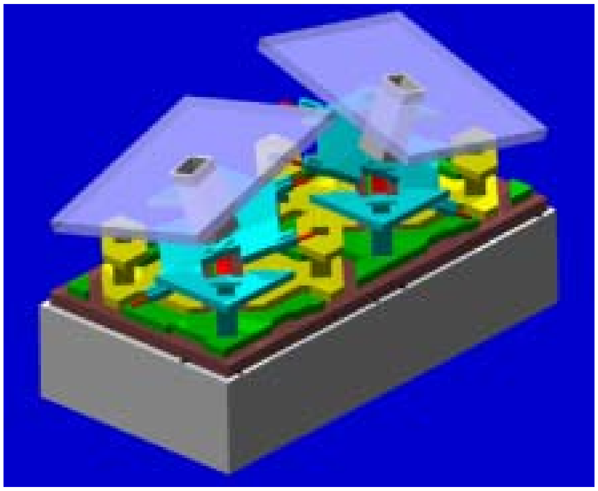

Figure 3. Schematic of two mirror-pixels comprising a typical SBG light modulator consisting of 1024 x 768 individually addressable mirror-pixels.

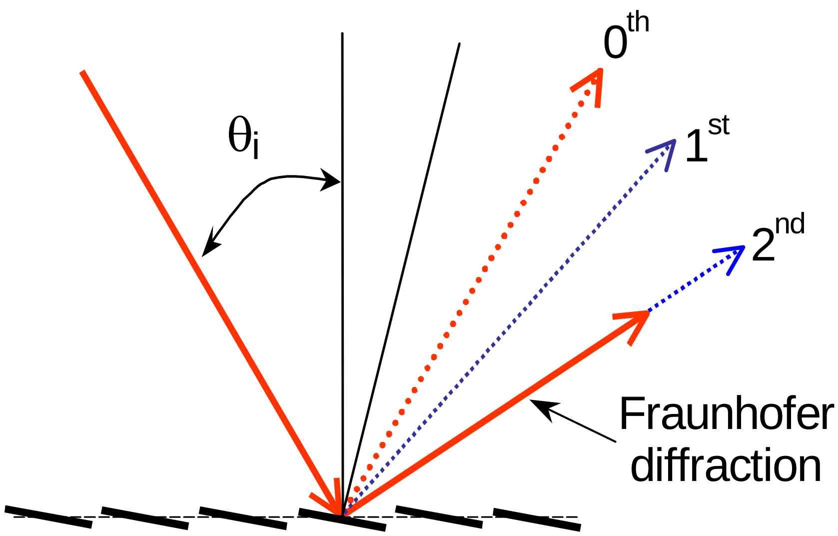

Figure 4. Incident light hitting SBG mirror-pixels under the "blazed" grating condition. Most of the diffracted radiation is concentrated in the second order producing a highly efficient coherent light modulator.

behavior of the SBG is evident for both coherent and incoherent sources but is more obvious in coherent monochromatic sources as discrete well-resolved diffractive peaks are observed in the reflective power distribution.

Another consideration in using a pixelated modulator with a coherent monochromatic beam is the relationship between intensity and the number of pixels turned "on" or "off". In a typical single-mode fiber application, the gaussian beam from the fiber is focused onto the SLM by means of a focusing lens. The light, which is reflected or transmitted by the modulator, is then collimated and focused back into a single-mode fiber. By turning "on" various pixels in the spatial light modulator, the amount of optical power coupled into the receiving fiber for each wavelength is varied. The coupling of power into the output fiber, however, is not straightforward since it is dependent upon the power of the overlap integral between the modulated field and the mode of the output fiber [1]. Thus, the coupled power is given by:

$$P_r = \left| \iint F_s(x,y) F_f^*(x,y)\, dx dy \right|^2$$

where $F_s(x,y)$ and $F_f(x,y)$ are the complex fields of the modulated signal and the fiber mode, respectively. It is important to note that the efficiency of the fiber coupling depends not only on the amplitude of the two fields, but on how well they are matched in phase. It can be shown that a similar relationship can be derived at either the input to the fiber, at the collimated beam, or at the spatial light modulator.

The SBG is suitable for applications where a series of parallel optical switches (e.g. 700,000 - 1x2 switches) are required. An illustrative optical system useful for processing DWDM signals and incorporates a SBG is depicted in Figure 5. An input/output medium (typically a fiber or array of fibers), a dispersion element (typically a grating), and the SBG comprise the optical system. Attenuation functions in the system are achievable by switching pixels between +1 and –1 states to control the amount of light directed to the output coupler (e.g. with mirrors in +1 state). Monitoring can be achieved by detection of the light directed into the –1 state. In this configuration, minimum system insertion loss of about 4 dB has been demonstrated with approximately 35 dB maximum attenuation. Systems with polarization dependent losses of less than 0.2 dB have also been exhibited. Polarization dependent losses are limited by dispersive elements in these systems. With a ~15 microsecond switching speed, the SBG is well suited for dynamically balancing gain in optical networks.

3. RESULTS

Shown in Figure 6 is the intensity of an asynchronous spontaneous emission (ASE) source as transmitted through a optical system similar to Figure 5. The top trace is for all the mirrors in the SBG modulator on and the bottom trace is for all mirrors off. There is typically a 34 to 35 dB extinction ratio between the all-on versus all-off. In the middle trace the ASE power is equalized to approximately 31 dBm. The spectrum was equalized manually in this case and shows approximately a +/- 0.2 dB variation across the band. This system only uses approximately 150 mirrors to carry a 100 GHz wide band which limits the intensity resolution for equalization. Other designs using a few thousand mirrors per band are capable of much finer resolution.

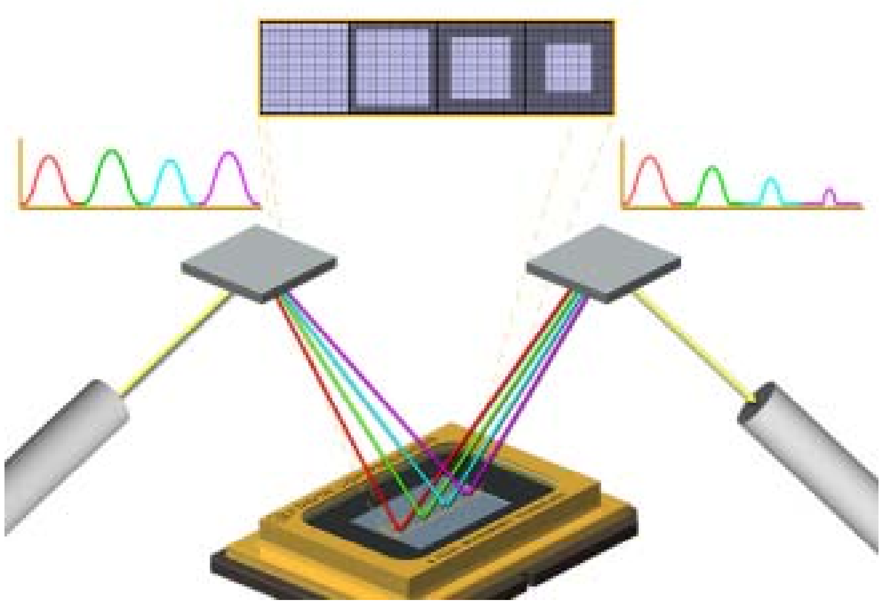

Figure 5. DLP™ SBG illuminated by several wavelength bands before and after attenuation.

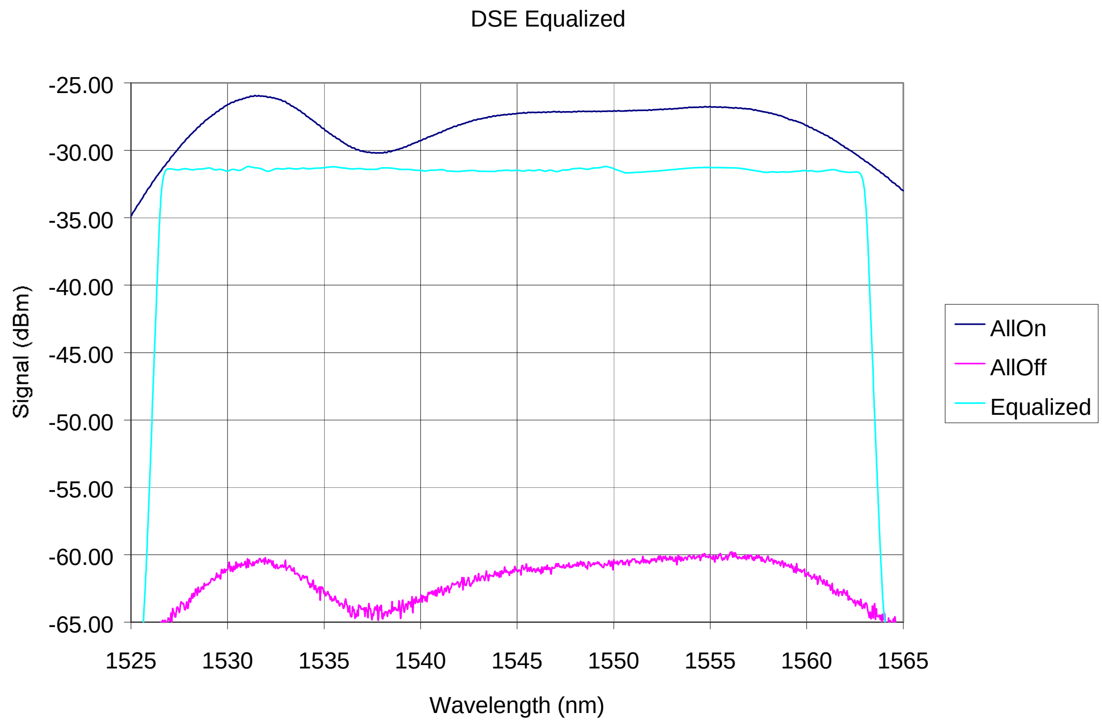

Figure 6. Equalized ASE spectrum.

The response function of a column of mirrors is shown in Figure 7. Note the abscissa of the graph is only 1.2 nm or 150 GHz. For this particular system approximately eight columns of mirrors are required to obtain full 35 dB of extinction. The small dip on the short wavelength side of the spectrum is the result of phase effects in the system.

An Optical Add Drop Multiplexer can be configured using a optical system similar to the one shown in Figure 5 by adding a second output coupler collecting the light corresponding to the –1 mirror state. Figure 8 shows the performance of a system configured like that in Figure 5 that is configured in an optical add drop function. As the modulator is a highly parallel 1x2 switch this implementation uses one mirror state (e.g. +1) as an pass (express) channel and the other position (-1) as a drop or add channel. 50 GHz separates channels in this system. An optical performance monitor can also be configured similarly by placing a detector at the position of the output fiber in Figure 5. In this case the SBG mirrors are switched between states to decode wavelength and intensity signals arriving at the detector.

4. CONCLUSIONS

As a coherent light modulator, the SBG device can be used in DWDM optical networks to dynamically manipulate and shape optical signals. Systems exhibiting low insertion loss can

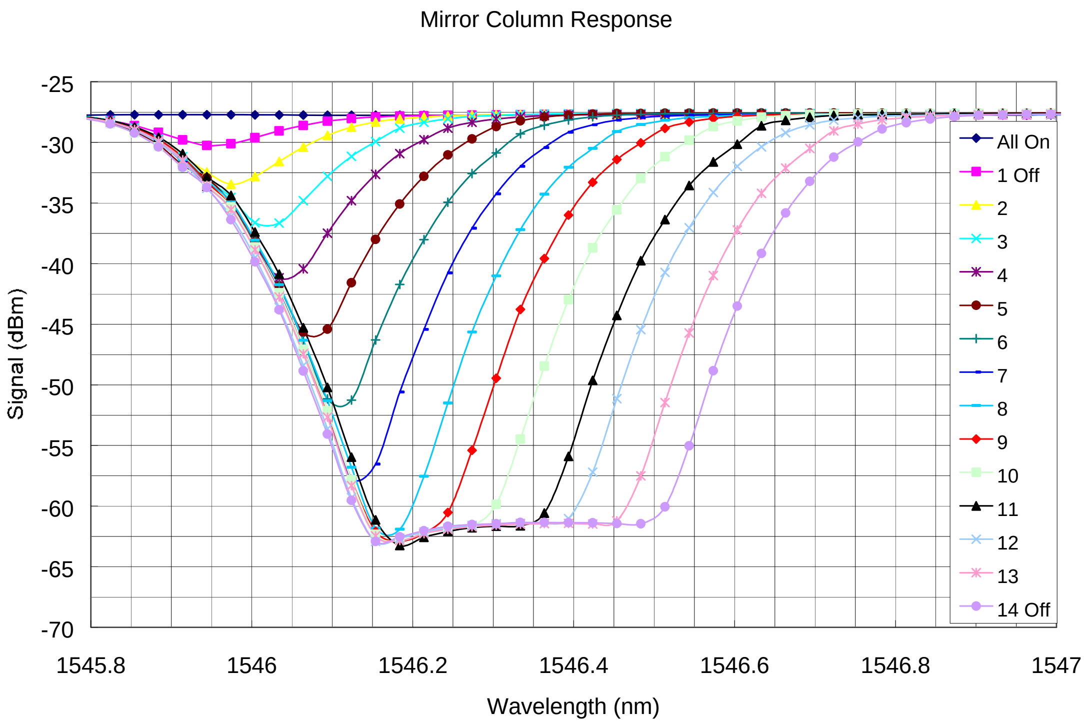

Figure 7. Mirror column response.

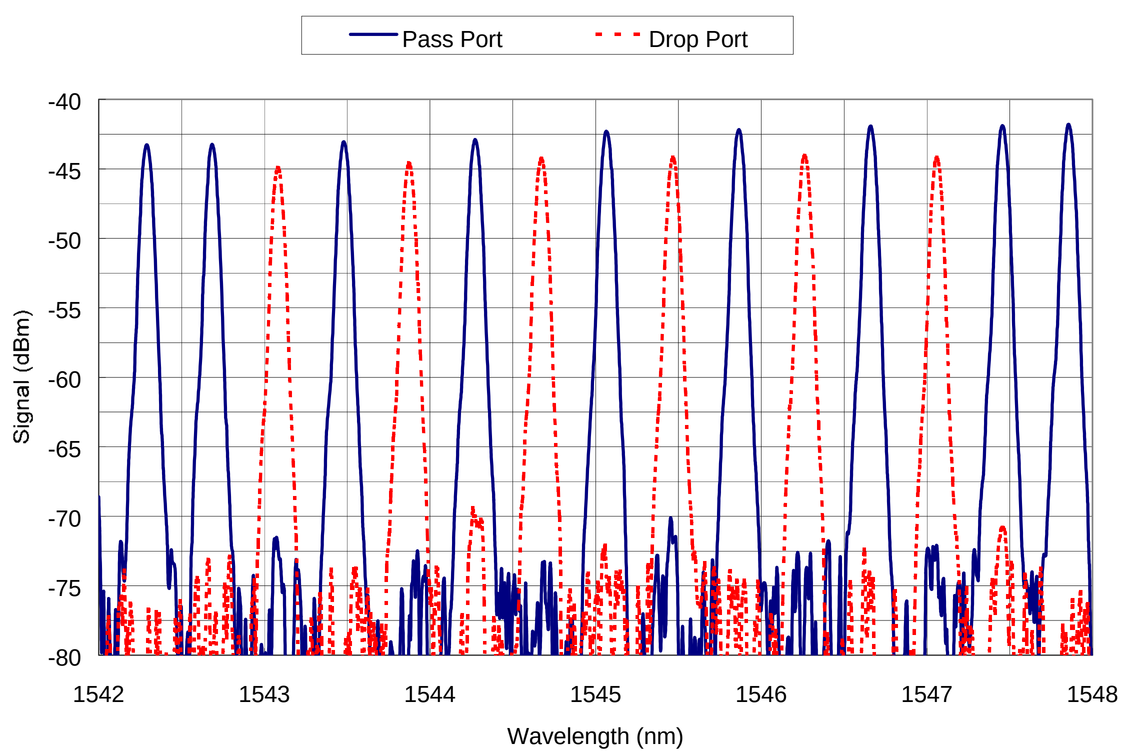

Figure 8. Performance of system configured as add drop.

be achieved by designing mirror arrays to meet blaze conditions such that the mirror tilt angle coincides with a diffractive order determined by the mirror pitch.

REFERENCE

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