Phase-Tunable Low-Loss, S-, C-, and L-Band DPSK and DQPSK Demodulator

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***Abstract*—Differential phase-shift keying (DPSK) and differential quadrature phase-shift keying (DQPSK) are touted as performers and reliable advanced modulation formats for next-generation optical transmission systems. One key device enabling such systems is the delay interferometer, converting the signal phase information into intensity modulation to be detected by the photodiodes. We developed an all-fiber delay-line interferometer for DPSK and DQPSK demodulation in the S-, C-, and L-band with low insertion loss, low-birefringence, and greater than 30 dB of extinction ratio over 100 nm and 20 dB from 1460 to 1640 nm in a single device. The device also features insensitivity to mechanical vibration, very low port imbalance (0.1 dB), and very low time delay between all outputs (0.1 ps). The device is highly reliable with a demonstrated failure-in-time rate of less than 100.**

***Index Terms*—Differential phase-shift keying (DPSK), differential quadrature phase-shift keying (DQPSK), delay line interferometer, Mach–Zehnder interferometer.**

I. Introduction

DIFFERENTIAL phase-shift keying (DPSK) in its different flavors is becoming one of the formats of choice in the deployment of next-generation optical communication systems for 40 Gb/s and transoceanic transmission systems [1], [2]. The benefits of using DPSK and DQPSK as alternatives to intensity modulation for the improvement in receiver sensitivity and tolerance to chromatic dispersion and certain nonlinear effects have been demonstrated.

A DPSK receiver requires of an optical delay-line interferometer (DLI) [3] followed by a balanced receiver to take advantage of the 3-dB optical signal-to-noise ratio (OSNR) advantage. DLI have also been found to be useful in optical network monitoring [4]. Normally, a DLI will have a one-bit delay to provide complete interference over a bit period [5] although recent reports indicate that in the presence of improper optical filtering and chromatic dispersion, a bit delay shorter than one-bit may be advantageous [6], [7]. Although several techniques can be used to implement the DLI, a fused fiber solution offers optimal optical performance from the point of view of insertion loss, extinction ratio, port imbalance, ambient vibration tolerances, tunability, and bandwidth. Wideband operation of DLIs is of interest since it allows a single component to be used for any of the ITU-defined transmission windows, namely the S-band (short) 1460–1530 nm, the C-band (common) 1530–1575 nm, and the L-band (long) 1575–1625 nm. A wideband device does not only provide significant inventory cost reduction but it may also be necessary for future dynamically reconfigurable networks utilizing the full low-loss window of silica fibers [8].

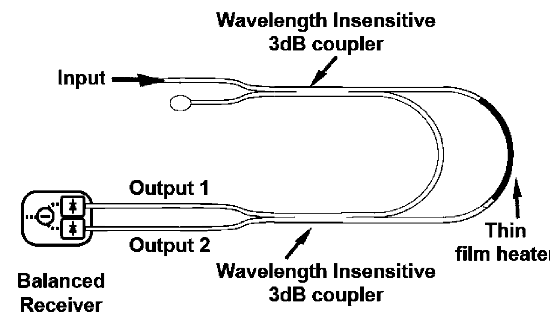

Fig. 1. Schematic of the ITF Labs/Avensys DPSK demodulator using WICs. The wide bandwidth of the WICs allow for S-, C-, L-, and U-band operation.

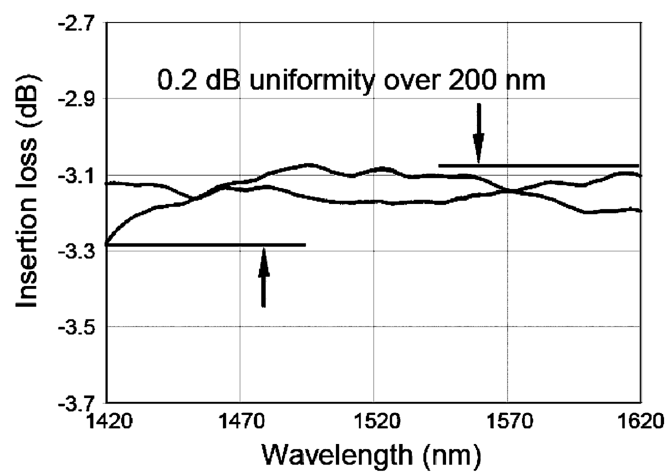

Fig. 2. Typical measured WICs using asymmetric fibers and group velocity equalization to obtain flat response close 180 nm of bandwidth.

In this letter, we present an all-fiber ultra-wideband DPSK and DQPSK demodulator capable of operating over 180 nm of bandwidth. The demodulator typically provides 0.3-dB insertion loss (not including connectors losses if connectors are used), 0.05 dB of polarization-dependent loss (PDL), typical polarization-dependent frequency shift of 1% of the free spectral range (FSR), and 30 dB over 100 nm and 20 dB from 1460 to 1640 nm of extinction ratio. The DPSK demodulator is slightly smaller than a business card at 42 mm × 87 mm × 6.5 mm. The

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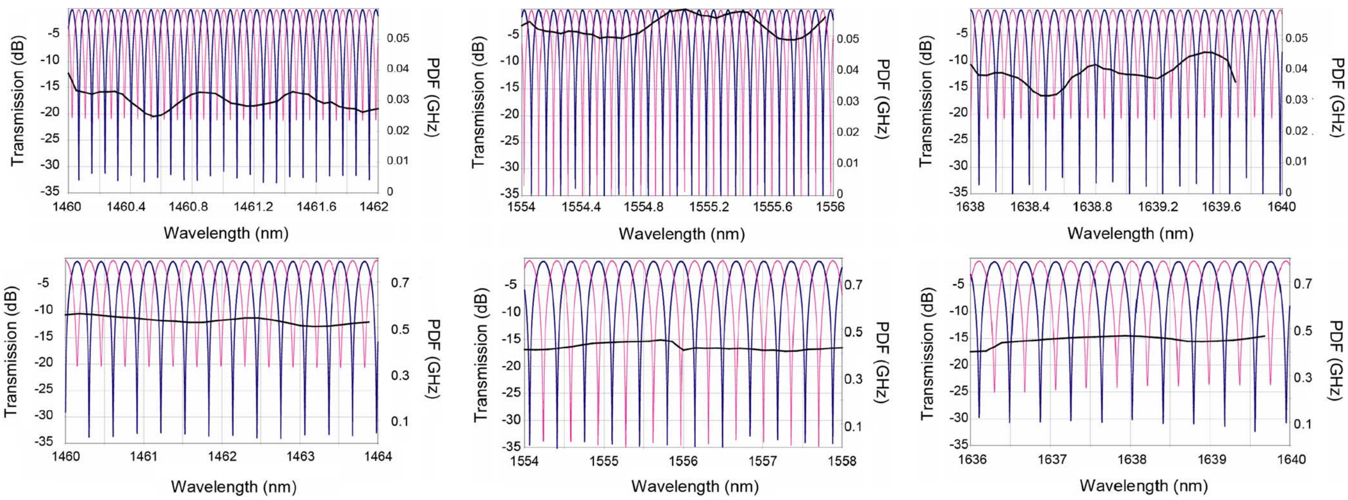

Fig. 3. Transmission spectra for a typical 12-GHz (top) and 43-GHz (bottom) DPSK demodulator at around 1460, 1555, and 1640 nm. Extinction ratio is kept higher than 20 dB over 180 nm of bandwidth. Insertion loss and PDf are low without much variation across the band.

device also has very low port imbalance of less than 0.1 dB, defined as the difference in insertion between the two output ports for two adjacent transmission peaks. Differential delay between output ports of less than 0.1 ps is easily achieved.

II. Theory

In a free-space Mach–Zehnder interferometer, beam splitters are used to separate and recombine the light wave. Ideally, a 50/50 splitting ratio would provide infinite extinction ratio when no polarization effect is present. Free-space beam splitters and antireflection coatings can be wavelength-dependent which restricts the bandwidth over which adequate extinction ratio can be obtained. In the all-fiber implementation, illustrated in Fig. 1, fiber couplers act as beam splitters. Although they are usually wavelength-sensitive, we proposed and demonstrated wavelength-independent couplers (WICs) [9] using asymmetric optical fibers. The optical properties of fused tapered components are determined by their transverse and longitudinal index profiles. Fused fiber couplers being modal interferometers, their spectral response is oscillatory with a period of oscillation defined by: $\Lambda = \lambda^2/(L\Delta n_g)$, where Λ is the period of oscillation, λ the wavelength, and Δn_g the difference between group index of two propagating modes in the coupler, namely SLP_{01} and SLP_{11}. By carefully choosing the fiber diameter, fusing ratio and tapering profile, a coupler structure where the group velocities of SLP_{01} and SLP_{11} are equalized can be designed such that Δn_g is zero and the spectral oscillation period is infinite providing a flat spectral response [9]. The transmission results for a typical WIC are shown in Fig. 2 where the wavelength dependency is flat within 0.2 dB over 200 nm of spectral bandwidth.

III. Experimental Results

As illustrated in Fig. 1, the DPSK demodulator is comprised of two 3-dB WICs with a specified delay between them. The DQPSK demodulator is made of two identical DPSK demodulators at the two outputs of a 3-dB WIC.

Results for two typical demodulators with FSR of 12- and 43-GHz DPSK are presented in Fig. 3. FSR and insertion loss

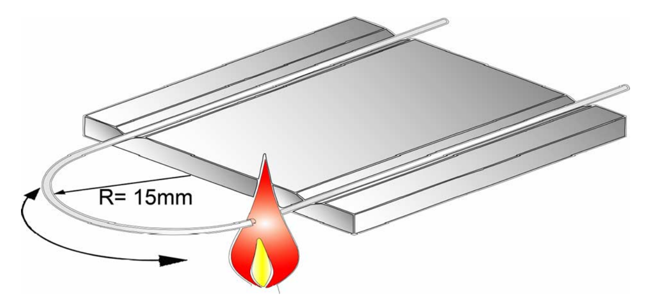

Fig. 4. Heat forming method to release photoelastic effect induced birefringence while ensuring long-term reliability of the demodulators.

are found to be very stable from 1460 to 1640 nm while the minimum extinction ratio is kept higher than 30 dB across 100 nm and 20 dB across 180 nm. Such an extinction ratio is more than enough to ensure that the signal is demodulated without penalty [5] since the interferometer provides port imbalance of much less than 0.1 dB.

IV. Bend Radius and Heat Forming

Bent fibers have mechanical stress which can lead to long-term stress corrosion with 25- to 32-mm bend radius being the minimum for untreated fibers. Another consequence of bending is the appearance of birefringence through the photoeleastic effect. Birefringence causes polarization dependency, leading to polarization-dependent OSNR penalties. A polarization-dependent frequency shift (PDf) value of 2.5% of FSR can lead to 0.5- and 3-dB OSNR penalty for DPSK and DQPSK, respectively [5]. We developped a heat forming technique illustrated in Fig. 4 using a flame to release the bend-induced stresses, thus minimizing birefringence and increasing fiber integrity. Following preforming, the fiber is in a permanent U-shape and experimental data shows that formed fibers have no loss and low PDL below 20 mdBs. The device is very reliable with a failure-in-time rate, the number of failures that can be expected in 10^9 hours of operation, of less than 100 (with typical 60% confidence level). Typical PDf values are 1% of FSR as illustrated in

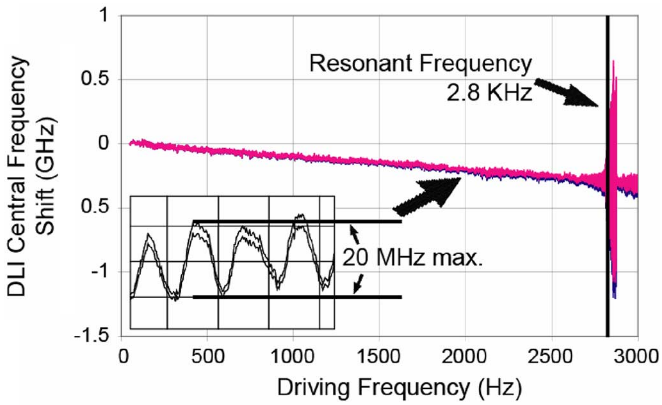

Fig. 5. Experimental demonstration of vibration insensitivity using sinusoidal vibration of 3g. Resonant frequency is well above 2 KHz and negligible frequency offset of only 20 MHz at 2 KHz.

Fig. 3, translating into insignificant penalty for DPSK and small penalty for DQPSK [5].

V. Tunability Efficiency and Time Constant

Silica-based DLIs typically drift by 1.25 GHz/°C. Although athermal DLI are feasible [10], tuning is still required to accommodate laser frequency offset making an athermal design of little use. A maximum 6-GHz frequency drift over the lifetime of a laser would incur a significant penalty at 10 and 40 Gb/s. The phase of the interferometers can be actively controlled to accommodate for laser frequency and temperature through a thin-film heater directly deposited on the optical fiber as shown in Fig. 1. The phase change is created through the thermooptic effect such that the tuning is proportional to the power being dissipated (or the square of the applied voltage). Very low power consumption is required to cover temperature ranges from -5 °C to 80 °C, typically below 0.250 W. Since the length of the heater is the same for all FSRs, the tuning efficiency scales with $0.2 \times$ FSR GHz/V^2. The tuning time constant is defined as the time required to tune to 63.2% of the requested frequency, irrespective of the frequency shift requested. This time constant is typically 230 ms (or 150 ms to reach 50%). The implication when using dithering to stabilize the demodulator is that using a higher frequency will require a larger driving amplitude for the same frequency dithering. Faster time constants are feasible because of the correlation between efficiency and speed. The demodulator can be modeled as an RC circuit with time constant $\tau = RC$. By improving the heat dissipation (reducing the R) in the demodulator, efficiency and time constant are reduced. A time constant of 50 ms (35 ms to reach 50%) has been achieved by reducing the efficiency by a factor of 3.

VI. Mechanical Vibrations Insensitivity

Fiber interferometers can potentially exhibit high microphonic sensitivity. A solution is to encapsulate the fiber structure but the technique also reduces the tuning efficiency since each supporting point conducts heat away from the fiber. A careful optimization was carried out to maintain vibration insensitivity from 0 to 2000 Hz, the telecom standard. Finite-element analysis for 125-μm fibers indicates that equidistant points separated by 14.75 mm are required for the resulting lowest eigenmode resonance to have a resonance of 2830 Hz. The lowest resonance is for motion perpendicular to the plane of the substrate.

We verified the design experimentally by testing a DLI under a sinusoidal vibration sweep from 5 to 3000 Hz at 3g amplitude. The measurement is performed by tuning a narrow line laser to the 3-dB point of the interferometric transmission and monitoring both output ports in order to verify vibration insensitivity. Although all axes of vibration were tested, only the perpendicular axis exhibited resonance in the tested range, as predicted by numerical analysis. Fig. 5 illustrates the experimental resonant frequency of 2.8 kHz matching the predicted value of 2830 Hz. We also tested the device in the presence of a constant sine vibration of 3g amplitude and frequency of 2000 Hz. The results were a p-p amplitude of only 20 MHz in optical frequency, well below any measurable penalty for frequency offset [5].

VII. Conclusion

We have developed an ultra-wideband DPSK and DQPSK demodulator for the S-, C-, and L-band which can operate over 180 nm of bandwidth. The device not only provides significant inventory cost reduction but may also be necessary for future dynamically reconfigurable networks. The device has low loss, low polarization dependence, insensitivity to mechanical vibrations, and high extinction ratio of 20 dB over 180 nm and 30 dB over 100 nm. The typical time constant is 230 or 150 ms to reach the halfway point.

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