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Abstract: A new topology that generates a DC voltage whose value is depending on the phase difference of two input RF signals is presented. It is implemented by the mixer concept. With the use of microwave photonics, the mixer-based phase detector can be operated over a very wide frequency range. It also has the advantages of high phase detection resolution, small phase detection error, and small DC offset and phase offset. The phase detector can be constructed using off-the-shelf components including a single integrated optical modulator and a low-speed balanced detector. Measured results on the phase detector demonstrate a 0° to 180° RF signal phase difference detection range for 3.5 GHz to 18 GHz input RF signal frequencies, less than ±3° phase detection error and 2° phase detection resolution.

Index Terms: Phase detector, microwave signal phase detection, optical modulator, balanced detector, bias controller, microwave photonics.

1. Introduction

Recently there is a growing interest in using microwave photonic techniques to measure RF signal parameters such as power, instantaneous frequency and phase difference [1]. This is because microwave photonics can overcome the bandwidth and speed limitation in electronic devices. It is also immune to electromagnetic interference. Measuring the instantaneous frequency of an RF signal and the phase difference of two RF signals are important in defence and telecommunication applications. Comparing to instantaneous frequency measurements [2], [3], there is less focus on using microwave photonic techniques for phase difference measurements. Reported microwave photonic based phase difference measurement techniques rely on using either an electrical spectrum analyser [4], an oscilloscope [5] or an optical power meter [6] to determine the phase difference of two input RF signals. This not only increases the system cost but also prevents the device to be used in phase locked loops, phase shift keying and frequency hopping systems where a DC voltage representing the RF signal phase difference is needed.

In electronic, a phase detector can be implemented by a mixer. The basic idea is two identical-frequency RF signals where their phase difference needs to be measured, are applied to the two mixer input ports. A DC voltage, which has a value depending on the two input RF signal phase difference, is generated at the mixer output port. When the two RF signals are in phase (out of
phase), the mixer output DC voltage has a positive (negative) maximum value. When they have a 90° phase difference, under an ideal situation, the mixer output DC voltage is zero volts. The idea of a mixer-based phase detector can be implemented using microwave photonic techniques. There are few reports on microwave photonic based phase detectors. While the phase detector based on a dual-series Mach Zehnder modulator (MZM) configuration is simple, the separation between two MZMs causes a phase offset [7]. A transmission line, which introduces a time delay that is the same as that caused by the two MZM separation, needs to be inserted at the second MZM RF input port to eliminate the phase offset [8]. The phase detector based on a dual-parallel MZM requires a reference electrical source and an electrical single sideband modulator, which limits the phase detector bandwidth [9]. The phase detector based on four-wave mixing (FWM) effect in a semiconductor optical amplifier requires two different-wavelength optical sources and an optical filter to select the nonlinear component generated by the FWM process [10]. It has a high phase detection error of around 10°. A dual-drive Mach Zehnder modulator (DDMZM) can be used to detect the phase difference of two RF signals [11]. A phase detector implemented using a DDMZM only involves a laser, a modulator and a photodiode. However, it has a DC offset, which causes signal distortion when it is used in a phase locked loop to demodulate a frequency modulation signal [12].

In this paper, we present a phase detector based on a single integrated optical modulator and a low-speed balanced detector. The phase detector can be operated over a very wide frequency range using the currently available components. This overcomes the bandwidth limitation in electronic phase detectors. Furthermore, it has high phase detection resolution and small DC offset and phase offset. The phase detector performance including DC offset, maximum output DC voltage, resolution, phase detection error and isolation between ports are investigated. Experiments have been conducted to verify the concept of the proposed phase detector. The results demonstrate that the phase detector has a wide operating frequency range of 3.5 GHz to 18 GHz and a 0° to 180° phase detection range with errors of less than ±3°. A 2° phase detection resolution and a stable performance are also demonstrated.

2. Operation Principle and Simulation Results

Fig. 1 shows the structure of the proposed microwave photonic based phase detection system. Continuous wave light generated by a laser source is launched into a dual-polarisation dual-drive Mach Zehnder modulator (DP-DDMZM). The DP-DDMZM is formed by two DDMZMs connected in parallel and a 90° polarisation rotator. Two input RF signals, which have the same angular frequency $\omega_{RF}$ and a phase difference $\varphi$, are fed into a power splitter and a 180° hybrid coupler as shown in the figure before injecting into the two null-biased DDMZMs. The polarisation state of the bottom DDMZM output optical signal is rotated by 90° via a 90° polarisation rotator. The two orthogonal linearly polarised optical signals at the DP-DDMZM output are split by a polarisation beam splitter (PBS). The electric field at the two PBS outputs can be expressed using Jacobi-Anger
expansion and are given by

\[ E_{\text{in}}(t) = \frac{1}{2\sqrt{2}} E_{\text{in}} e^{j\omega t} \mathbf{e}^{j\theta t} \left[ (-1 - \gamma_1) J_0 (\beta_{\text{RF}}) - J_1 (\beta_{\text{RF}}) e^{-j\omega t} + J_1 (\beta_{\text{RF}}) e^{j\omega t} + J_2 (\beta_{\text{RF}}) e^{-2j\omega t} \right] + J_2 (\beta_{\text{RF}}) e^{2j\omega t} \right] 
\]

\[ -\gamma_1 J_2 (\beta_{\text{RF}}) e^{-2i(\omega t+\phi+\pi+\theta)} - \gamma_1 J_2 (\beta_{\text{RF}}) e^{2i(\omega t+\phi+\pi+\theta)} \right] \]

\[ E_{\text{out}}(t) = \frac{1}{2\sqrt{2}} E_{\text{in}} e^{j\omega t} \mathbf{e}^{j\theta t} \left[ (-1 - \gamma_2) J_0 (\beta_{\text{RF}}) - J_1 (\beta_{\text{RF}}) e^{-j\omega t} + J_1 (\beta_{\text{RF}}) e^{j\omega t} + J_2 (\beta_{\text{RF}}) e^{-2j\omega t} \right] + J_2 (\beta_{\text{RF}}) e^{2j\omega t} \right] 
\]

\[ -\gamma_2 J_2 (\beta_{\text{RF}}) e^{-2i(\omega t+\phi) - \gamma_2 J_2 (\beta_{\text{RF}}) e^{2i(\omega t+\phi)} \right] \]

where \( E_{\text{in}} \) is the electric field amplitude of the light into the DP-DDMZM, \( t_{\text{RF}} \) is the DDMZM insertion loss, \( \omega_c = 2\pi f_c \) is the optical carrier angular frequency, \( \beta_{\text{RF}} = \pi V_{\text{RF}}/V_b \) is the RF signal modulation index, \( V_{\text{RF}} \) is the voltage of the RF signal into the RF port of the DDMZM, \( V_b \) is the modulator RF switching voltage and \( J_n(x) \) is the Bessel function of the first kind of \( n \)th order. There are two main non-ideal effects that affect the system performance. They are the amplitude imbalance in the two arms of the DDMZM and the phase imbalance in the 180° hybrid coupler. Therefore, a scaling factor \( \gamma_{1,2} = (\epsilon_{1,2}^{1/2} - 1)/(\epsilon_{1,2}^{1/2} + 1) \), which has a value between zero to one, and a 180° hybrid coupler phase imbalance \( \theta \) are included in (1) and (2), where \( \epsilon_{1,2} \) is the top and bottom DDMZM extinction ratio respectively. Note that the sidebands above the second order sidebands are neglected in (1) and (2) as they have small amplitudes. The output optical signals are detected by a low-speed balanced detector, which consists of a pair of photodiodes and a transimpedance amplifier. The average photocurrent generated by the top and bottom photodiode inside the balanced detector are the product of the average optical power into the top and bottom photodiode \( P_{\text{ave}1} \) and \( P_{\text{ave}2} \) and the photodiode responsivity \( \mathbf{e} \). They can be obtained from (1) and (2), and are given by

\[ I_{\text{ave}1} = \frac{1}{8} P_{\text{ave}1} \left[ (1 + \gamma_1^2 - 2\gamma_1) J_0^2 (\beta_{\text{RF}}) + 2(1 + \gamma_1^2) J_1^2 (\beta_{\text{RF}}) + 2(1 + \gamma_1^2) J_2^2 (\beta_{\text{RF}}) \right] \]

\[ + 4\gamma_1 J_1 J_2 (\beta_{\text{RF}}) \cos (\phi + \theta) - 4\gamma_1 J_2 J_2 (\beta_{\text{RF}}) \cos (2\phi + 2\theta) \]

\[ I_{\text{ave}2} = \frac{1}{8} P_{\text{ave}2} \left[ (1 + \gamma_2^2 - 2\gamma_2) J_0^2 (\beta_{\text{RF}}) + 2(1 + \gamma_2^2) J_1^2 (\beta_{\text{RF}}) + 2(1 + \gamma_2^2) J_2^2 (\beta_{\text{RF}}) \right] \]

\[ - 4\gamma_2 J_1 J_2 (\beta_{\text{RF}}) \cos (\phi) - 4\gamma_2 J_2 J_2 (\beta_{\text{RF}}) \cos (2\phi) \]

where \( P_{\text{ave}} \) is the optical power of the light into the DP-DDMZM. The DC voltage at the output of the balanced detector is given by

\[ V_{\text{DC}} = (P_{\text{ave}1} - P_{\text{ave}2}) \mathbf{e} \mathcal{R} \mathbb{G} \]

where \( \mathcal{R} \) is the transimpedance amplifier gain (V/A). In an ideal situation, the modulator extinction ratio is infinity and hence \( \gamma_1 = \gamma_2 = 1 \), and the 180° hybrid coupler has no phase imbalance, i.e., \( \theta = 0° \). Hence (5) can be written as

\[ V_{\text{DC,ideal}} = J_1^2 (\beta_{\text{RF}}) P_{\text{ave1}} \mathbf{e} \mathcal{R} \mathbb{G} \cos (\phi) \]

(6) shows the system output DC voltage has a cosine relationship with the phase difference of the two input RF signals. Therefore, the input RF signal phase difference can be determined from the system output DC voltage. Since the output DC voltage is also dependent on the RF signal modulation index, which in turn dependent on the input RF signal voltage, the input RF signal voltage needs to be known in order to determine the RF signal phase difference. This is also required in the reported electronic- and photonics-based phase detectors [7]-[10], [13], [14]. Alternatively, the phase detector can be operated at the saturated mode to reduce the input RF signal voltage dependence on the phase detector output DC voltage [8]. Note that the maximum output DC voltage and the phase slope are determined by the gain of the transimpedance amplifier inside the balanced detector. A commercial balanced amplified photodetector (Thorlabs PDB440C) has a high transimpedance gain of 51 kV/A. This enables a high maximum positive and negative DC voltage of ±0.9 V to be generated at the phase detector output without the need of using an optical amplifier to amplify the output optical signal. Hence a high-resolution phase detection can
be obtained. Since only the system output DC voltage is of interest, no length matching in the two paths between the PBS and the balanced detector is needed.

In practice, all MZMs have a finite extinction ratio and the bias drift problem. Additionally, all hybrid couplers have a phase imbalance. These non-ideal effects cause the relationship between the system output DC voltage and the RF signal phase difference behaves differently to a cosine function, which leads to phase detection error. According to (5), when the two DDMZMs have an extinction ratio of 30 dB and 35 dB, the maximum phase detection error is $5.7^\circ$ in a $30^\circ$-$150^\circ$ RF signal phase difference range. The maximum phase detection error reduces to $1.9^\circ$ when the extinction ratio of the two DDMZMs are above 40 dB. Commercial modulator bias controllers can be included in the phase detector shown in Fig. 1 to stabilise the operating points of the two DDMZMs. They also enable a high extinction ratio of more than 50 dB to be obtained [15]. This simultaneously reduces the phase detection error caused by amplitude imbalance in the two arms of the DDMZMs and the modulator bias drift. The effect of the $180^\circ$ hybrid coupler phase imbalance on the DP-DDMZM based phase detector was investigated. Fig. 2(a) shows the average photocurrent at the output of the top and bottom photodiodes for various input RF signal phase differences when the $180^\circ$ hybrid coupler has no phase imbalance and a $6^\circ$ phase imbalance. It can be seen from the figure that a $6^\circ$ phase imbalance in the $180^\circ$ hybrid coupler causes slight reduction in the photocurrent generated by the top photodiode. In this case, the system output DC voltage, which can be obtained using (5) and is shown by the dashed line in Fig. 2(b), is different to the ideal system output DC voltage shown by the solid line in the figure. The DC offset, which is the phase detector output voltage when the two input RF signals have a $90^\circ$ phase difference, is $-46.3$ mV for the phase detector having a maximum positive and negative output DC voltage of $\pm0.9$ V. Fig. 2(b) also shows a $2^\circ$ change in the RF signal phase difference causes around $30$ mV change in the output DC voltage at the linear $40^\circ$-$140^\circ$ phase detection region. Outside this linear phase detection region, there is at least $1$ mV change in the output DC voltage for every $2^\circ$ change in the RF signal phase difference. A $1$ mV change in a DC voltage can be detected by a commercial digital multimeter (DMM), e.g., Keysight U1230 series handheld DMM. Hence a high-resolution phase detection of $2^\circ$ can be obtained.

The red dotted line in Fig. 3(a) shows, when the $180^\circ$ hybrid coupler has a $6^\circ$ phase imbalance, the phase detector has a typical phase detection error of $-3^\circ$ and the phase detection error is within $\pm4^\circ$ over the $2^\circ$-$178^\circ$ RF signal phase difference range. The figure also shows the typical phase detection error is half the $180^\circ$ hybrid coupler phase imbalance. According to the simulation results shown in Fig. 3(a), using a $2$-$26.5$ GHz and $12$-$67$ GHz bandwidth $180^\circ$ hybrid coupler that has a maximum phase imbalance of $\pm5^\circ$ [16] and $\pm10^\circ$ [17] in the proposed structure results in a typical
Fig. 3. Phase detection error versus RF signal phase difference for (a) different 180° hybrid coupler phase imbalances while the RF signal modulation index is fixed at 0.3, and (b) different RF signal modulation indexes while the 180° hybrid coupler phase imbalance is fixed at 6°.

Fig. 4. Experimental setup for measuring the DP-DDMZM based phase detector output photocurrent at the (a) top and (b) bottom PBS output. PC: polarisation controller; 90° PR: 90° polarisation rotator; PD: photodiode.

Phase detection error of ±2.5° and ±5° respectively. A phase trimmer can also be inserted at a 180° hybrid coupler output port to reduce the coupler phase imbalance, which consequently improves the phase detection accuracy. Fig. 3(b) shows the phase detection error remains almost the same for different RF signal modulation indexes. This indicates that the phase detector has almost the same performance over a wide input RF signal power range of -13.9 dBm to 11.2 dBm for a DDMZM having an RF switching voltage of 4 V. Note from Fig. 3(a) and (b) that there is a large change in the phase detection error when the RF signal phase difference is between 170° and 180°. The reason behind this large phase detection error change is that the phase detector is operating outside the linear phase detection region. Hence a small variation in the output DC voltage indicates a large change in the RF signal phase difference. Although the change in the phase detection error in the 170°-180° RF signal phase difference region is large, the phase detection error is within -3° to 4.5° when a 180° hybrid coupler with 6° phase imbalance is used in the proposed structure, as can be seen in Fig. 3(b).

3. Experimental Results
An experiment was set up as shown in Fig. 4(a) to verify the concept of the proposed phase detection system. Due to the lack of a balanced detector, the average optical power at each...
PBS output was measured one after another by a photodiode inside a bias controller. They were subtracted manually and multiplied with a photodiode responsivity of 0.85 A/W and a 51 kV/A transimpedance amplifier gain to obtain a DC voltage, which is equivalent to that obtained using a balanced detector. The optical source was a tunable laser (Keysight N7711A) operating at a wavelength of 1550 nm and an optical power of 13 dBm. A polarisation controller (PC) was connected after the tunable laser to align the polarisation state of the light to the slow axis of a polarisation maintaining fibre before launching to a DP-DDMZM (Fujitsu FTM7980EDA). The extinction ratio of each DDMZM inside the DP-DDMZM was measured in advance with the use of a bias controller (Plugtech MBC-MZM-01). An extinction ratio of 47.5 dB and 50.6 dB was obtained for the top and bottom DDMZM respectively. The top and bottom DDPMZM were biased at the null point via a bias controller and a DC power supplier as shown in Fig. 4(a). A 10 GHz RF signal generated by a signal generator was split into two via a power splitter. Each of the two RF signals passed through an electrical phase shifter (EPS) (ATM P1507), which had an adjustable group delay of 0 to 0.17 ns. The power splitter and the EPSs were used to emulate two RF signals with a phase difference. The two RF signals were injected into the top DDMZM via 180° hybrid couplers. Note that a 180° phase shift was introduced to one of the RF signals by a 180° hybrid coupler, which is equivalent to using a 180° hybrid coupler to split an RF signal as shown in Fig. 1. Also note that one of the 180° hybrid coupler outputs was connected to a network analyser to monitor the change in the two RF signal phase difference when the EPS group delay was adjusted. The two RF ports of the bottom DDMZM were terminated by 50 Ω terminators. Therefore, only a small residual optical carrier was presented at the bottom DDMZM output. The PC at the output of the DP-DDMZM was adjusted to ensure the optical signal at the top DDMZM output was routed to the top PBS output as shown in Fig. 4(a). The PC can be avoided by using a polarisation maintaining fibre between the DP-DDMZM and the PBS. The PBS output containing the top DDMZM output optical signal was detected by the bias controller built-in photodiode. The average output optical power was displayed on a computer connected to the bias controller.

The power of the 10 GHz RF signal into the DDMZM was measured to be 1.5 dBm. Since the DDMZM had an RF switching voltage of 3.5 V at 10 GHz, the RF signal modulation index was 0.34. An RF signal phase difference of 0° to 180° was introduced to the system by adjusting the group delay of the EPS followed by the 180° hybrid coupler that had an output connected to the network analyser. The average output optical power was measured on the bias controller built-in photodiode. The average photocurrent, which is the product of the average optical power and the photodiode responsivity, for various RF signal phase differences is shown in Fig. 5(a). The above process was repeated by injecting the RF signals into the bottom DDMZM through the 0° port of the 180° hybrid coupler and measuring the average output optical power at the bottom PBS output port.
Fig. 6. Measured and simulated (solid line) phase detector output DC voltage for the 10 GHz RF signals having a power of -1.4 dBm (blue squares), 1.5 dBm (red dots) and 4.4 dBm (pink stars) into the DDMZMs. The corresponding modulation indexes are 0.24, 0.34 and 0.47.

The phase detection error can be found by comparing the RF signal phase differences obtained from the measured and simulated output DC voltages. It is less than ±2.4°, ±1.7° and ±1.6° for the input RF signal power of -1.4 dBm, 1.5 dBm and 4.4 dBm respectively.

Fig. 7. Measured (blue dots) and simulated (solid line) average photocurrent generated by the photodiode connected to the (a) top and (b) bottom PBS output. The RF signal modulation index is 0.34.

Excellent agreement can be seen. The system output average photocurrent is ranged from 0 μA to 16.6 μA. The system output DC voltage can be obtained using (5) with the average photocurrents shown in Fig. 5 and a transimpedance amplifier gain of 51 kV/A. The measured and simulated output DC voltage are shown by the red dots and a solid line respectively in Fig. 6. The above measurement was repeated for -1.4 dBm and 4.4 dBm RF signal powers into the DDMZMs. The results are shown in Fig. 6. The figure shows the DC offset is less than 7.8 mV for all three cases. The phase detection error can be found by comparing the RF signal phase differences obtained from the measured and simulated output DC voltages. It is less than ±2.4°, ±1.7° and ±1.6° for the input RF signal power of -1.4 dBm, 1.5 dBm and 4.4 dBm respectively.

The phase detection resolution of the proposed structure was examined. Fig. 7 shows the average photocurrents generated by the photodiode connected to the top and bottom PBS output for an RF signal phase difference range of 40°-60°. The output DC voltages obtained from the average photocurrents are shown in Fig. 8(a). The measurements were repeated for an RF signal phase difference range of 120°-140° and the corresponding output DC voltages are shown in Fig. 8(b). The results shown in Fig. 8 reveal that the proposed phase detector can achieve 2° phase detection resolution. The phase detector average output optical powers were monitored over a period of time when the two input RF signals had a 60° phase difference. The phase detector output DC voltages were obtained based on the average output optical powers and are shown in Fig. 9. It can be seen from the figure that there is less than 2.1 mV output DC voltage fluctuation via the bias controller built-in photodiode as shown in Fig. 4(b). The result is shown in Fig. 5(b). The simulated average photocurrents obtained using (3) and (4) are also shown in the figures. Excellent agreement can be seen. The system output average photocurrent is ranged from 0 μA to 16.6 μA. The system output DC voltage can be obtained using (5) with the average photocurrents shown in Fig. 5 and a transimpedance amplifier gain of 51 kV/A. The measured and simulated output DC voltage are shown by the red dots and a solid line respectively in Fig. 6. The above measurement was repeated for -1.4 dBm and 4.4 dBm RF signal powers into the DDMZMs. The results are shown in Fig. 6. The figure shows the DC offset is less than 7.8 mV for all three cases. The phase detection error can be found by comparing the RF signal phase differences obtained from the measured and simulated output DC voltages. It is less than ±2.4°, ±1.7° and ±1.6° for the input RF signal power of -1.4 dBm, 1.5 dBm and 4.4 dBm respectively.

The phase detection resolution of the proposed structure was examined. Fig. 7 shows the average photocurrents generated by the photodiode connected to the top and bottom PBS output for an RF signal phase difference range of 40°-60°. The output DC voltages obtained from the average photocurrents are shown in Fig. 8(a). The measurements were repeated for an RF signal phase difference range of 120°-140° and the corresponding output DC voltages are shown in Fig. 8(b). The results shown in Fig. 8 reveal that the proposed phase detector can achieve 2° phase detection resolution. The phase detector average output optical powers were monitored over a period of time when the two input RF signals had a 60° phase difference. The phase detector output DC voltages were obtained based on the average output optical powers and are shown in Fig. 9. It can be seen from the figure that there is less than 2.1 mV output DC voltage fluctuation.
Fig. 8. Measured (blue dots) and simulated (solid line) output DC voltage for an RF signal phase difference between (a) 40°-60° and (b) 120°-140°.

Fig. 9. DC voltages obtained from the average output optical powers measured over 10 minutes for the 10 GHz input RF signals with 60° phase difference.

TABLE 1
Phase Detection Error Obtained for Different Input RF Signal Frequencies

| Frequency (GHz) | Phase detection error (Degree) |
|-----------------|-------------------------------|
| 3.5             | ±1.4                          |
| 8               | ±2.8                          |
| 10              | ±1.7                          |
| 13.5            | ±1.7                          |
| 18              | ±1.5                          |

over 10 minutes. A stable output DC voltage with less than 2.5 mV fluctuation over 10 minutes was also observed for an RF signal phase difference of 140°. These small output DC voltage fluctuations cause less than 0.3° phase detection errors.

In order to demonstrate the phase detector is capable to operate over a wide frequency range, the phase detector output average photocurrents were measured for different input RF signal frequencies. The input RF signal power was adjusted accordingly as the RF signal frequency changed so that the modulation index was around 0.34. The phase detector output DC voltage was obtained using the average photocurrents. The maximum phase detection error found from the output DC voltages for different input RF signal frequencies were summarised in Table 1. The results demonstrate that the proposed structure can detect an RF signal phase difference with less than ±3° error over a frequency range of 3.5 GHz to 18 GHz, which is comparable to the phase detection error estimated from the output DC voltage measurement given in [9]. The DC offset was
less than 8.8 mV. Finally, the isolation between the two phase detector input ports was measured by connecting the input RF port of the two DDMZMs to the network analyser. An over 45 dB isolation was obtained over the 3.5-18 GHz frequency range.

4. Conclusion
A new microwave photonic topology that produces a DC voltage related to the phase difference of two input RF signals has been presented. It is based on a DP-DDMZM and a low-speed balanced detector. The proposed phase detector can be operated over a wide frequency range and has only little DC offset. Incorporating a modulator bias controller in the proposed structure not only can produce a stable output but also reduces the phase detection error caused by amplitude imbalance in the two arms of the DDMZM. Unlike many microwave photonic signal processing and measurement structures, path length matching for balanced detection is not required because only the system output DC voltage is of interest. Commercial low-speed balanced detectors have a high transimpedance amplifier gain. This enables the phase detector to have a large maximum positive and negative output DC voltage and hence a high-resolution phase detection can be achieved without using an optical amplifier to increase the average output optical power. The new phase detector has been experimentally verified for different-frequency and different-power-level input RF signal. The results demonstrate the DP-DDMZM based phase detector has a wide operating frequency range of 3.5 GHz to 18 GHz with a small DC offset of less than 8.8 mV and phase detection error of less than ±3°. A 2° phase detection resolution and over 45 dB isolation between ports were obtained. The new microwave photonic based phase detector can be operated at any required microwave frequency and is readily extendable to millimetre wave band.

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