Photonic crystal phase detector

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In a recent article, it was shown that side-coupled photonic crystal (PhC) cavity arrays had dark and bright states depending upon the relative phase between the excitation optical sources. We show that the existence of dark and bright states in these arrays can be used to develop a phase detector, which can find applications in optical differential phase-shift-keying demodulation systems. © 2008 Optical Society of America

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1. INTRODUCTION

Integrated optical devices and systems are essential for harnessing the full potential of photonics including transmission and manipulation of data at very high speeds. In order to fabricate these integrated optical devices, light must be confined in very small regions by using either total internal reflection [1–5] or a periodic bandgap effect [6–12]. The ability to forbid the propagation of light in a certain wavelength range (periodic bandgap effect) can be used to engineer the flow of light in many different ways. Introduction of defects to these structures enable one to inject or extract light in a controlled way. Thus, by introducing defects, it is possible to create optical waveguides and cavities in microscale and nanoscale ranges and couple these structures to conventional optical devices.

Besides potential applications in computers, defense, and biology, integrated optical devices will have a major impact in communications. Typical optical communication systems employ on–off shift-keying modulation scheme to modulate the optical carrier. However, in recent years, differential phase-shift keying (DPSK) has emerged as a promising modulation scheme for optical communications [13–15]. DPSK data format exhibits improved receiver sensitivity and higher tolerance to fiber nonlinearities. A typical DPSK modulator uses phase or Mach–Zehnder modulators for signal processing. Recently, a microring modulator was used to generate DPSK signals [15]. On the other hand, typical DPSK modulators use delay-line or microring interferometers to attain the differential phase-shift-keying operation [15].

In a recent article [12], Chak and coworkers showed that it was possible to create dark and bright states in photonic-crystal (PhC) microcavity arrays. These arrays could create low-group-velocity bright states and high-group-velocity dark states. The creation of these states depended upon the relative phase between the sources, which inspired us to use these arrays as phase detectors. We modify the multicavity array to enable it to detect the relative phase between two optical sources, with potential applications to the demodulation of DPSK signals.

In order to convert this phase detector into a DPSK demodulator, we can use the system illustrated in Fig. 1. In this figure, the incoming DPSK signal is divided into two signals with equal power levels by a 3 dB splitter, but with one of the signals being further delayed by a bit period with a delay line (an optical fiber cable, for example). These two DPSK signals (direct and delayed) enter the phase detector. The phase detector will convert the relative phase information between these two signals into an on–off shift-keying stream. This on–off shift-keying stream can then be easily demodulated by a photodetector, and the original information can be recovered. In this article, we will limit our analysis to the phase detector.

2. ANALYSIS OF THE PHASE DETECTOR

In order to confine light in the vertical direction, we use the epitaxially layered structure shown in Fig. 2(a). It consists of a GaAs core, an oxidized lower cladding, and a GaAs substrate. The thickness of the GaAs core is 140 nm, and the thickness of the oxidized layer is 450 nm (before oxidation takes place). The oxidized and air regions confine light in the GaAs core region. This epitaxially layered structure is designed to operate under transverse electric (TE) modes, with main magnetic field component along the y direction (see Fig. 2(b) for details about the Cartesian coordinates employed in this article).

Because of the large dimensions of this phase detector, our simulations will be based upon two-dimensional finite-difference time-domain (FDTD) methods, with an effective index of 2.82.

The PhC where the phase detector will be built-in consists of a square lattice of air holes with lattice constant \( \Lambda = 317 \text{ nm} \). The air holes have a radius of 120 nm. In or-
der to assess the performance of this phase detector, two sources are placed in the same $x$ position but in different input waveguides (A and B). These input waveguides will transport the optical fields to the single-defect cavity array, as shown in Fig. 2(b). Depending upon the relative phase between these sources, the cavities will be either excited (bright state) or nonexcited (dark state).

In the dark state, the coupled resonators are not excited by the two input waveguides, whereas in the bright states, these coupled cavities are excited. Since the excitation of these states depends upon the relative phase of the input signals, this property will be used on the development of the phase detectors. More details about these states can be found in [12].

Two small slots close to the bends of the input waveguides optimize the transmission of light through the bends [16]. If there is no coupling of light into the cavities, light will continue to propagate into the bent waveguides without experiencing much reflection. Moreover, small slots may indirectly contribute to the coupling of light into microcavities.

A single-defect microcavity in a square lattice of air holes has just a whispering gallery mode in its bandgap region. This mode has odd symmetry with respect to the $x$ axis, i.e., the four lobes of this mode have opposite phases with respect to the center of the cavity and to the $x$ axis. Hence we may expect that, if the sources are in-phase, they will not strongly excite these cavities, but if they have opposite phases, the cavities will be strongly excited and will carry power into the output waveguide (E). This is what actually happens for the phase detector shown in Fig. 2(b). The spectrum at the output waveguide (E) is shown in Fig. 3(a). The main peak appears at $\lambda = 1038$ nm ($\lambda$ is the free-space wavelength), with a quality factor of 650. There is another peak at $\lambda = 1061$ nm, but the PhC is off its bandgap region. At $\lambda = 1038$ nm, and when the sources are out-of-phase, about 51% of the total input power is coupled into the output waveguide, as can be observed in Fig. 3(b). Now, when these sources are in-phase at $\lambda = 1038$ nm, only 2% of the input power is coupled into the waveguide, as can be observed in Fig. 3(c). Hence, it is expected that this phase detector will be able to convert relative phases into relative amplitudes, with extinction ratios (ER)—meaning ratio of power at high level to the power at low level—higher than 20. The ER is defined as

$$ER = \frac{P_{180°}}{P_{0°}},$$

where $P_{180°}$ is the transmitted power into the waveguide when the two sources are out-of-phase and $P_{0°}$ is the transmitted power into the waveguide when the two sources are in-phase.

The relative power transmitted into the output waveguide as a function of the relative phase between the sources is shown in Fig. 4. The maximum power is transmitted to the waveguide when the relative phase between the two sources is 180°, and the minimum power is transmitted to the waveguides when the sources are in-phase. Based upon the curve presented in Fig. 4, it can be observed that the phase detector is not very sensitive to changes in the relative phase between the sources; in fact, there is a slow change of the transmitted power as a function of their relative phase (a rate of about 0.27% of the total input power for each degree change in the relative phase). Also, this phase detector has phase symmetry with respect to 180°, i.e., it produces the same amount of transmitted power for angles $\theta$ and $\theta+180°$.

In some situations, the power divider in Fig. 1 can be unbalanced and unevenly divide the power in the output ports. We examine the dependence of an unequal power in the output arms of the power divider on the ER of the phase detector. The power ratio is defined as the power in the output with highest power divided by the power in the other output port. We observe that, initially, an uneven distribution of power improves the ER (reaching a maximum for a power ratio of two) but eventually decreases as the power ratio increases, as shown in Fig. 5. At high values of power ratio, the power in one of the sources will be
much larger than in the other port, enabling the excitation of the microcavities despite the phase between the sources (the dark state seems to be the result of the interference between the two sources).

The number of cavities in the phase detector also influences its performance. For example, if there is just a single cavity in the phase detector, power can be directly coupled into the waveguide and not via the single-defect PhC microcavity. In this case, the ER is just 2.7 because of parasitic coupling into the waveguide. Figure 6 shows the ER as a function of the number of cavities at a wavelength close to 1040 nm. It can be observed that, for a few cavities the ER is low because of parasitic coupling into the waveguide, but the ER reaches saturation after five cavities in the phase detector (the saturation can be explained by the “considerable” reduction of the parasitic coupling into the output waveguide). The number of peaks in the wavelength range between $\lambda = 1000$ nm and $\lambda = 1100$ nm also depends upon the number of microcavities. In general the greater the number of microcavities, then the larger is the number of resonant peaks in this wavelength range. The peak close to $\lambda = 1040$ nm changes from $\lambda = 1033$ nm and $\lambda = 1038$ nm but is without any general trend with the number of cavities in the array, i.e., the peak wavelength oscillates between being blue-shifted and red-shifted with the number of cavities.

The number of holes between distinct microcavities in the array ($N_{\text{cav}}$) defines the spacing and coupling strength between the different cavities. $N_{\text{cav}}$ affects the quality factor (Q) of the peak around $\lambda = 1040$ nm and the number of

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Fig. 3. (a) Magnetic field ($H_y$) spectrum at the center of the output waveguide (E). (b) Magnetic field distribution ($H_y$) for out-of-phase sources. (c) Magnetic field distribution ($H_y$) for in-phase sources. In parts (b) and (c), $\lambda = 1038$ nm.

Fig. 4. Relative power transmitted into the waveguide as a function of the relative phases between the sources at $\lambda = 1038$ nm.

Fig. 5. Extinction ratio (ER) as a function of the power ratio in the output arms of the power divider.
peaks in the phase detector. $Q$ increases with the number of holes between the cavities until the point when the cavities are weakly coupled and act as nearly independent resonators, leading to a saturation of $Q$. This can be clearly observed in Fig. 7(a). Apparently, if the coupling is stronger, it is easier to lose power into the waveguide, leading to lower values of $Q$.

The ER is also affected by the number of holes between adjacent microcavities. In a case of one hole between adjacent cavities, light can be easily coupled into the waveguide for either a dark or bright state, which results in a low value of ER. The ER increases when the number of holes between adjacent cavities increases, reaching a maximum value for $N_{\text{cav}}=2$. When $N_{\text{cav}}$ is greater than two, less power is coupled into the waveguide in the bright state, thus leading to lower values of ER. This can be clearly observed in Fig. 7(b), where the ER starts to decrease for $N_{\text{cav}}>2$.

We finally analyze the effects of having a different number of holes between the input cavities and the first microcavity in the array ($N_{\text{cg}}$). $N_{\text{cg}}$ determines the coupling strength into the microcavity array; if the coupling is strong, light will be easily coupled into the microcavity array; otherwise light will prefer to propagate through the bent input waveguides (C and D). Figure 8(a) shows the percentage of the total input power that is coupled into the waveguide when the sources are out-of-phase. From this figure, we observe that light can be easily coupled into the output waveguide (E) when the number of holes ($N_{\text{cg}}$) is 1 or 2. However, when $N_{\text{cg}}>2$ the coupling into the microcavity array is difficult and light “prefers” to continue in the bent waveguides (C and D). Figure 8(b) shows the magnetic field distribution at $\lambda=1038$ nm and when the sources are in-phase. Although the microcavities are still excited, not much power flows into the output waveguide. The power flowing through the bent waveguides (C and D) is significantly higher, since it is easier for light to continue in the waveguide.

Fig. 7. (a) Quality factor ($Q$) of the peak close to $\lambda=1040$ nm as a function of the number of holes between adjacent cavities ($N_{\text{cav}}$). (b) Extinction ratio (ER) as a function of $N_{\text{cav}}$.

Fig. 8. (a) Out-of-phase coupling efficiency as a function of the number of holes between the input waveguides (A and B) and the first microcavity in the array ($N_{\text{cg}}$). (b) Magnetic field distribution ($H_y$) for the situation when the sources are out-of-phase and $N_{\text{cg}}=3$. 
We believe that, based upon the results presented in this article, this device can operate as a phase detector and can be used in DPSK demodulators. Further work is under way to assess the performance of this phase detector in a real DPSK demodulator, especially when noise is included.

3. CONCLUSIONS

A photonic crystal phase detector was presented in the article. It will convert phase variations between distinct sources into amplitude variations. These amplitude variations stem from the fact that an array of microcavities in the PhC has bright and dark states that can initiate coupling of light into the output waveguide. Owing to its simplicity and compact nature, this phase detector can find potential applications in DPSK demodulation systems.

REFERENCES