The Proposal of Pulse Synchronous Laser Signal Source Based on Coupled-microdisk Photonic Molecules

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Abstract— Here we propose a model to generate pulse synchronous laser signals based on waveguide coupled microdisk photonic molecules. Through the beating between the symmetric and anti-symmetric modes in the photonic molecules, dual pulse synchronous laser signals are coupled out from two waveguides. We simulate the light field distributions of the modes in the photonic molecules via finite difference time domain (FDTD) method, and compute the frequency differences between the symmetric mode and anti-symmetric transverse magnetic (TM) coupled modes. The frequency differences, which represent the pulse repetition frequency (PRF) of pulse synchronous laser signals, can reach from dozens of GHz to about 1 THz according to the simulation. The numerical results show that the proposed model can generate dual pulse synchronous laser signals with fixed pulse widths and complementary phase which can act as a pulse synchronous laser signal source.

1. INTRODUCTION

During the past twenty years, photonics molecules (PMs) which consist of clusters of electromagnetically coupled optical microcavities have been drawing a great attention for their distinctive optical properties [1]. Photonic molecules with different configurations or patterns are applied to realize variety kinds of photoelectronic devices, such as microlasers, sensors, and compact photonics information processing. On the other hand, in the radar system, transmitter utilize pulse synchronous signals to control different amplifier chains and modulation switch triggering time [2]. These pulse synchronous signals must keep a strict sequential relationship to make sure the transmitters operate properly. In addition, the synchronization between transmitter and indicator depends on pulse synchronous signals. With the determination range, especially the speed determination, being continuously expanded, pulse synchronous signals with higher PRF are needed.

In this paper, we analyze the operation of the waveguide coupled microdisk photonic molecules by the finite-difference time-domain (FDTD) method. The microdisk photonic molecules can generate dual pulse synchronous laser signals with fixed pulse widths and complementary phase from two coupled waveguide, through the beating between the symmetric and anti-symmetric coupled modes [3]. The PRF, which is equal to the frequency difference between the two beating modes, can be controlled by varying the gap between two microdisks. The results show the waveguide coupled microdisk photonic molecules can act as a pulse synchronous laser signal with PRF at microwave band.

2. MODEL FOUNDATION AND ANALYSIS

We study the waveguide coupled microdisk photonic molecules by the two-dimensional FDTD method and focus on the interaction between the symmetric and anti-symmetric coupled modes. In the following simulation, we only consider the transverse magnetic (TM) modes. Figure 1 shows the schematic diagram of the two-dimensional waveguide coupled microdisk photonic molecules . We set the radii of microdisk $R = 2\,\mu\text{m}$, the width of waveguide $d = 0.4\,\mu\text{m}$, the gap between the microdisk and corresponding coupled waveguide $s = 0.3\,\mu\text{m}$, and the variable parameter w represent the gap between two microdisks. We set the refractive index of the two microdisks resonators and two waveguides to 3.2, and they are all surrounded by air with a refractive index of 1.0. The blue rectangular frame is a 10-cell perfectly matched layer (PML) to terminate the simulation window. The waveguides are inserted to the PML to confirm the lightwave coupled into the waveguides can be detected as output optical signal and eliminate the influence of waveguide port reflection. The dashed line between two microdisks is the symmetry axis, and the mode coupling between two mcirodisk will results in coupled modes with symmetric or anti-symmetric field distributions relative to the symmetry axis. To excite the symmetric mode and the anti-symmetric mode separately, we set two symmetric exciting sources relative to the symmetry axis near the adjacent boundaries of the two microdisks, which are the red points in the Figure 1. The exciting source used in the FDTD simulation can be expressed as $P(t) = \exp[-(t-t_0)^2/t_w^2]\cos(2\pi ft)$, where t_0 and t_w are the times of the pulse center and the pulse half width respectively, and f is the center frequency of the pulse.

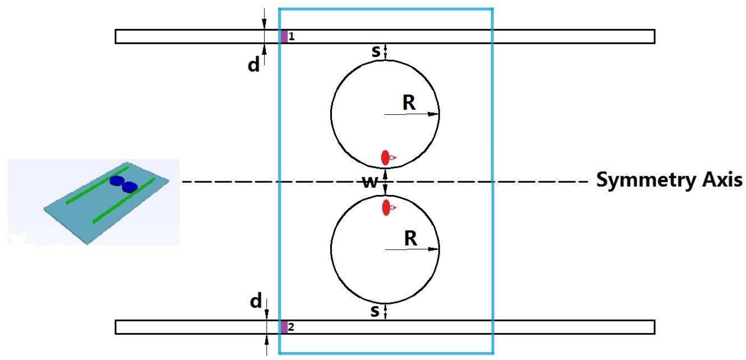

Figure 1: Schematic diagram of waveguide coupled microdisk photonic molecules for the FDTD simulation. (inset is 3D diagram).

At first, we using the symmetric and anti-symmetric sources to excite the symmetric and anti-symmetric modes respectively. The pulse sources covering a wide range of frequency are applied to excite all the considered TM modes, and then the Padé approximation method is used to calculate the intensity spectra from the time domain FDTD output. A 2.1×10^6-step FDTD simulation is performed with the mesh cell size of 20 nm, $t_w = 2^8\Delta t$, $t_0 = 2t_w$, $\Delta t = 4.67 \times 10^{-17}$ s and $f = 193.5$ THz. Through the simulation, we can get the intensity spectra of the waveguide coupled microdisk photonic molecules with different symmetry conditions. Figure 2(a) shows the intensity spectra from 203 THz to 210 THz when the gap between two microdisks $w = 0.3$ µm, from which we can find that there is obvious coupling induced mode splitting between the symmetric TM mode and the corresponding anti-symmetric TM mode. In fact, the mode splitting vary with w for different TM modes. This phenomenon has been observed by many study on common photonic molecules [4]. Thus, we can obtain the frequency difference between the symmetric mode and the corresponding anti-symmetric mode as a function of w. Figure 2(b) shows the frequency difference versus $w$for different TM modes. We can see that the frequency difference can reach from dozens of GHz to about 1 THz, but it decreases when w increases and would become zero when w is big enough for all the TM modes, at which time the coupling can be neglected. Nevertheless, for the forth-order mode $TM_{13,4}$, this trend is relatively flat because its evanescent field has a relatively large interaction area, especially when compared with that of the fundamental mode $TM_{23,1}$.

Utilizing the frequency difference produced by the coupling induced mode splitting, we can obtain optical microwave signal through the beating of the two nearly degenerate coupled modes. In

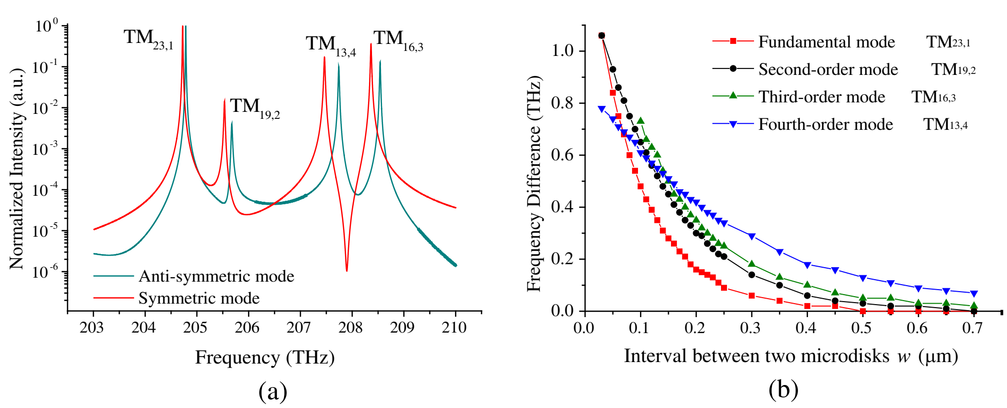

Figure 2: (a) Intensity spectra of the waveguide coupled microdisk photonic molecules with different symmetry conditions obtained by the FDTD simulation, where the radii of microdisk $R = 2$ µm, the width of waveguide $d = 0.4$ µm, the gap between microdisk and corresponding coupled waveguide $s = 0.3$ µm, and the gap between two microdisks $w = 0.3$ µm. (b) The variation of the frequency difference between the symmetric mode and the corresponding anti-symmetric mode with the gap between two microdisks w for different TM modes.

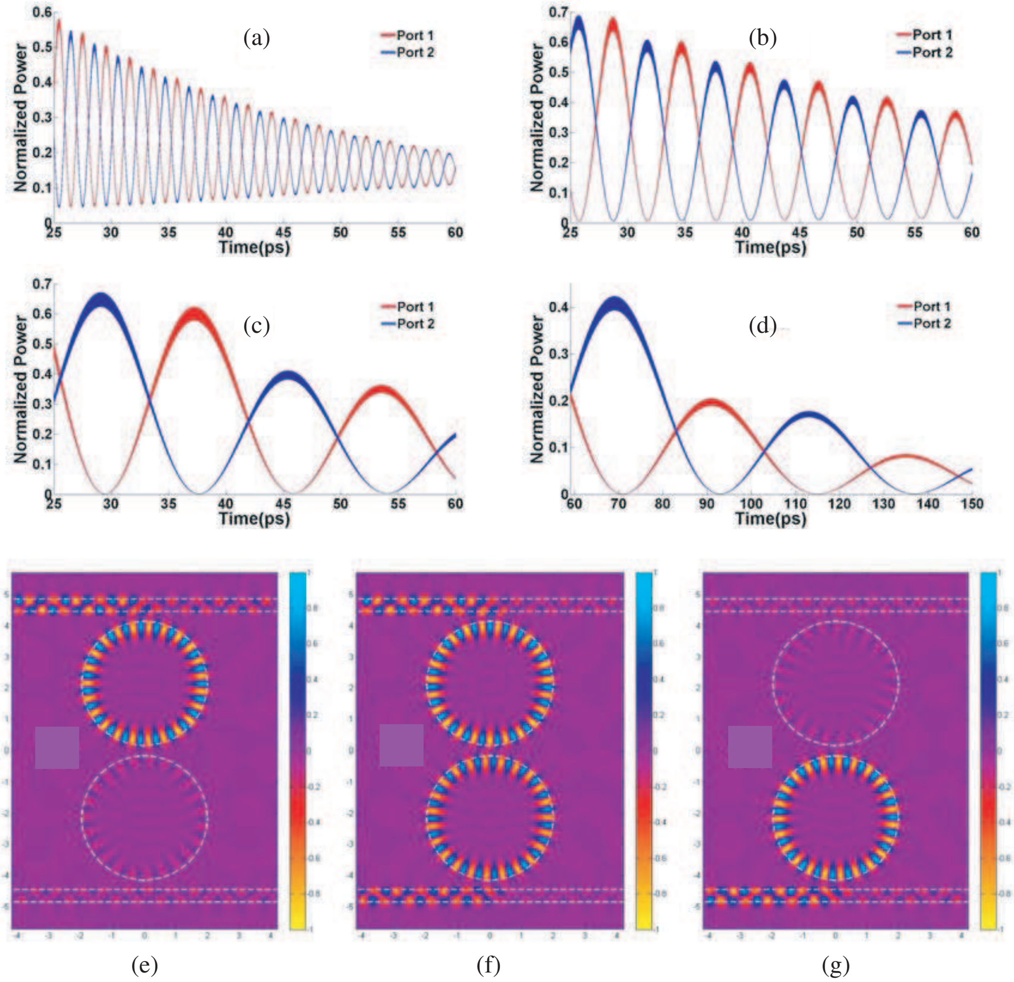

Figure 3: The oscillograms for the normalized power output at port 1 and port 2 with the gap between two microdisks w of (a) 0.1, (b) 0.2, (c) 0.3, (d) 0.4 µm, respectively; (e), (f), (g) the change of field distribution corresponding to the output converting between port 1 and port 2 with w of 0.3 µm.

either one of the two microdisks, when the symmetric mode and the corresponding anti-symmetric mode interact with each other, the time evolution of the produced light field has quasi-periodical character. If we assume that the symmetric mode frequency were f_1 and the corresponding anti-symmetric mode frequency were f_2, the produced intensity would vary with sinusoidal function at the beating frequency $|f_1 - f_2|$, namely the frequency difference of the two nearly degenerate coupled modes. According to the property of the symmetric and anti-symmetric modes, when their phase difference in one of the two microdisks is zero, the phase difference in the other one should be π. This property lead to the oscillating intensity in the two microdisks has an additional phase difference of $\pi/2$. That is to say, the light field not only oscillates quasi-periodically in either one of the two microdisks, but also oscillates between the two microdisks alternately. On this basis, the produced quasi-periodically alternate oscillatory signals can be output through the two waveguides which couple with the two microdisks respectively. Then these two sets of output signals form dual pulse synchronous laser signals, and the pulse repetition frequencies are equal to the beating frequency $|f_1 - f_2|$. To obtain the quasi-periodically alternate oscillatory signals, we excite the symmetric mode and the corresponding anti-symmetric mode at the same time. We use the exciting source with the pulse half width of $t_w = 2^{18}\Delta t$, which covers a narrow frequency range centered at the obtained mode frequency above, and detect the output power signals of the two waveguides at port 1 and port 2 respectively, which are shown in Figure 1 as purple rectangles. The (a), (b), (c), (d) in Figure 3 are the oscillograms for the normalized power output at port 1 and port 2 when the gap between two microdisks w are 0.1, 0.2, 0.3, 0.4 µm, respectively, whose repetition frequencies are 0.4862, 0.1675, 0.0614, 0.0227 THz. They are equal to the frequency differences shown in Figure 2(b), which are 0.48, 0.16, 0.06, 0.02 THz, respectively. Meanwhile, we can find that the phases of the output power at port 1 and port 2 are strictly complementary, namely, their phase difference remains $\pi/2$ as explained above. The Figures 3(e), (f), (g) show the change of E_y field distribution corresponding to the output converting between port 1 and port 2 when w is 0.3 µm, and the light field in the waveguides are amplified ten times for clearly. Obviously, the quasi-periodically alternate oscillatory output signals detected at port 1 and port 2 derive from the quasi-periodically alternate oscillation between the two microdisks.

On the other hand, we calculate the Q factors of these modes. Considering that the Q factor of the fundamental mode is much higher than that of the other modes, here we only give the Q factor of the fundamental mode versus w for the symmetric mode and the corresponding anti-symmetric mode, as shown in Figure 4. In the simulation, we set material absorption coefficient $\alpha = 10\,\mathrm{cm}^{-1}$, and the mode group index $n_g = 3.6$. The anti-symmetric mode has a larger Q factor than the symmetric modes. This is due to that the optical leakage to the exterior domain of the anti-symmetric mode is reduced by destructive interference, and, on the contrary, the optical leakage to the exterior domain of the symmetric mode is enhanced by constructive interference [5]. We can find that the difference of Q factors between the symmetric mode and the corresponding anti-symmetric mode tapers off, when the gap between two microdisks w increases. The difference may result in, compared with the situation that w is small, it is easier to excite the two nearly degenerate modes at the same time when w is relatively larger. Namely, it is easier to produce dual pulse synchronous laser signals when w is relatively larger. However, the mode splitting would drop off as w increases, which correspond to a smaller PRF. Therefore, we should choose the gap between two microdisks properly in practice.

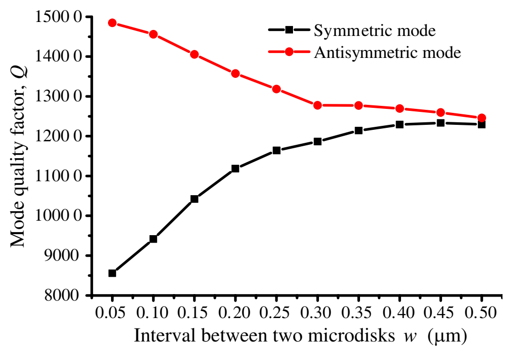

Figure 4: The Q factors of the fundamental mode $TM_{23,1}$ versus the gap between two microdisks w for the symmetric mode and the anti-symmetric mode.

3. CONCLUSION

This paper proposes a pulse synchronous laser signal source based on the waveguide coupled microdisk photonic molecules through the beating between the nearly degenerate symmetric mode and anti-symmetric coupled mode. We analyze the operation of the model by the finite difference time domain (FDTD) method. The pulse repetition frequency is equal to the beating frequency, that is the coupling induced frequency difference of the two nearly degenerate coupled modes, which could reach from dozens of GHz to about 1 THz and be controlled by the gap between two microdisks. Considering the influence of mode Q factor, we expect to optimize the model by replace the microdisk with microring in the follow-up study.

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