Coherent Microwave Generation in a Nonlinear Photonic Crystal

Yan-qing Lu, Min Xiao, and Gregory J. Salamo

***Abstract*—We propose a new approach for generating coherent microwaves in a nonlinear photonic crystal through optical rectification. In a photonic crystal, the reciprocal vector and dispersion of the group velocity can be used to both compensate for the velocity mismatch between the generated microwave and the pump light. We show that coherent microwave radiation from kilohertz to terahertz can be generated through this approach by designing a suitable structure.**

***Index Terms*—Coherent microwave, nonlinear photonic crystal, optical rectification, quasi-phase-matching.**

I. Introduction

OVER the last few decades, a great deal of attention has been given to materials with artificial periodic structures [1], i.e., superlattices. Among them are photonic crystals and quasi-phase-matched (QPM) materials. In a photonic crystal, the dielectric constant is varied periodically resulting in a dispersion relation that exhibits a band structure [2]. As a result, the propagation of light with a frequency in the band gap is suppressed. Some novel laser geometries [3], [4] and waveguide devices [5] have being constructed by making use of this frequency selectivity. Recent work on nonlinear photonic crystals has focused on the third-order nonlinearity [6]–[8]. While second-order nonlinear optical frequency conversion has not been well studied in such a structure [9], QPM materials—especially their most famous representative, periodically poled $LiNbO_3$ (PPLN)—have been carefully investigated [10], [11]. In PPLN or its analogs, the second-order nonlinear optical coefficient is periodically modulated, while its dielectric constant is uniform, leading to compensation of the phase mismatch between the input and the generated beams [11]. Due to the similarities in structure and some of the physical principles governing photonic crystals and QPM materials, a QPM material could be viewed as a special case of a nonlinear photonic crystal [12].

Among second-order nonlinear optical effects, optical rectification has been known for decades [13], but it has not been as widely studied as other nonlinear effects, such as second harmonic generation (SHG), difference-frequency generation (DFG), or optical parametric oscillation. However, recent reports show that optical rectification can be used to generate ultra-short electrical pulses with a high repetition rate [14], and terahertz radiation [15], [16].

In this paper, the optical rectification effect in a nonlinear photonic crystal is investigated. It is shown that coherent microwaves can be efficiently generated in a nonlinear photonic crystal through optical rectification. In addition, an intrinsic relationship between a nonlinear photonic crystal and a QPM material is established by considering optical rectification. The structural parameters of several coherent microwave sources are also calculated.

II. Theoretical Analysis

Although there is progress in generating coherent microwaves [17], [18], pursuing a highly efficient and simple coherent microwave source with good spatial and spectral characteristics is still a large challenge. Here, we consider optical rectification of a modulated light beam as a source of coherent microwaves. For a modulated light beam propagating through a nonlinear crystal, a modulated electric field is generated through optical rectification [14], so that every point where the pump light passes is a source of microwaves, where the frequency of the microwaves is determined by the repetition rate of the pump light. The generated microwaves will interfere with each other in any arbitrary direction, and the final microwave intensity along a specific direction depends on the relative phase difference between the microwaves. Obviously, if the light pulse's velocity is equal to the velocity of the microwave, all generated microwaves will interfere with each other constructively in the forward direction, and efficient coherent microwaves will be generated. Here, we should point out that it is the group velocity not the phase velocity of the pump light that should match the microwave's phase velocity, because it is the light pulses, and not the continuous wave (CW) light, that excites microwaves. Velocity matching is the prerequisite condition for coherent microwave generation through optical rectification. Unfortunately, for most materials, the optical refractive index is different from that of a microwave frequencies. The constructive interference condition thus cannot, in general, be fulfilled, making effective microwave generation difficult.

Two methods can be used to solve the velocity-matching problem: control of the group velocity of the pump light or control of the phase velocity of the microwaves. In this paper, we demonstrate that these two approaches can both be realized in a nonlinear photonic crystal.

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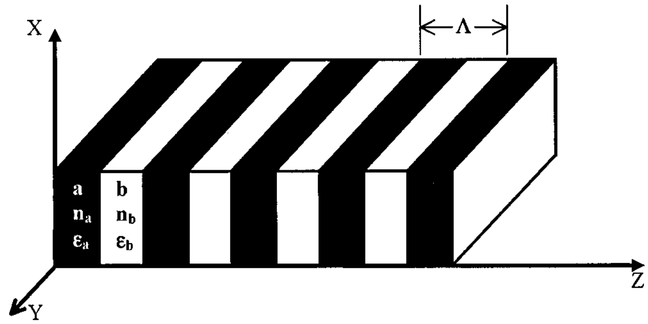

Fig. 1. Structure diagram of a nonlinear photonic crystal composed of two media: a and b.

In a photonic crystal, the group velocity of a light pulse changes with its frequency, especially near the photonic band gap. Thus, velocity matching by tuning the group velocity of the pump light pulse is possible. As for the microwave phase velocity, although it does not change as much as the group velocity near the band gap, an incident wave can be scattered and change its wave vector by a reciprocal vector. If we define the effective phase velocity as $\Omega/(k+G_m)$, where $\Omega,\, k,\, G_m$ represent the microwave frequency, wave vector and reciprocal vector, respectively, the velocities can be quasi-matched in a photonic crystal. This idea is much like QPM in nonlinear frequency conversion.

To demonstrate the predictions above, we consider a well-characterized nonlinear photonic crystal. The nonlinear photonic crystal should have a periodic dielectric constant. Furthermore, the material should have a second-order nonlinearity for establishing nonlinear optical effects. In general, the nonlinear optical coefficient should also vary periodically as the dielectric constant. Although the nonlinear photonic crystal could be 1-D, 2-D, or 3-D, we only consider the 1-D case, since it is the simplest and the results can be extended to 2-D and 3-D structures. Fig. 1 shows the typical structure of a nonlinear photonic crystal with a period of Λ that is composed of two kinds of media aligned periodically. The parameters $a,\, n_a,\, \varepsilon_a$ and b, and $n_b,\, \varepsilon_b$ are their thicknesses, refractive indices, and dielectric constants, respectively.

In order to generate microwaves through optical rectification, high repetition rate pump light needs to be available. In fact, 100-MHz repetition rate mode-locked laser light has been commercially available for many years. However, to simplify the analysis and to obtain higher repetition rates, here we propose that the modulated pump light is obtained from a single frequency CW laser after its intensity is modulated periodically through electrooptic (EO) modulation. We assume that the modulation frequency of the pump light could cover the wide range from kilohertz to terahertz.

The original plane wave propagates along the z direction with a frequency of ω_0 and is described as $E(z,\, t) = E_0 e^{i(\omega_0 t - k_0 z)}$, where k_0 is its wave vector. Considering the periodicity of the amplitude after modulation, it can be expanded as a Fourier series and written as

$$\begin{aligned}\psi(z,\, t) &= \frac{1}{2}\left\{\left[\sum_{m=0}^{\infty} c_m(z)\cos(m\Omega t + \delta_m)\right] e^{i\omega_0 t} + c.c\right\} \\ &= \frac{1}{2}\left\{\sum_{m=-\infty}^{\infty} \alpha_m(z) e^{i(\omega_0 + m\Omega)t} + c.c\right\} \qquad (1)\end{aligned}$$

where Ω is the modulation frequency that is much smaller than the light frequency ω_0 and the α_m and c_m depend on the amplitude of the modulation on the original light. From the expression above, the single-frequency wave becomes a pulsed light beam with various frequencies: $\omega_0 \pm \mathrm{m}\Omega$. However, since the pump light is obtained by the modulation of a plane wave, the intensity of light at ω_0 is expected to be much larger than that for the other Fourier components.

Although light of many different frequencies can emerge after modulation, they will not couple in a linear media. However, in nonlinear photonic crystals, every frequency of light may interact with each other and produce additional frequencies through nonlinear effects. Since optical rectification can be viewed as a special form of DFG, microwaves with frequencies at Ω, 2Ω, $3\Omega \cdots$, which are generated from optical rectification, are in fact produced by the interactions between the center frequency ω_0 and its sidebands at $\omega_0 \pm \mathrm{m}\Omega$. Here, study only the generation of microwaves at frequency Ω. There are two major ways to produce microwaves at frequency Ω. First, by DFG between $\omega_0 + \Omega$ and ω_0, and second, by the DFG between ω_0 and $\omega_0 - \Omega$. Since ω_0 constitutes the major part of the pump light, microwaves with the frequency Ω come mainly from the second method. Thus, the study of the generation of microwaves reduces to the study of the three-wave coupling process among three frequency components: ω_0, Ω and $\omega_1 = \omega_0 - \Omega$.

The total electric field intensity of these three waves can be written as

$$\begin{aligned}E &= E^{\omega_0} + E^{\Omega} + E^{\omega_1} \\ &= \frac{1}{2}\Big[E_0(z)e^{i(\omega_0 t - k_0 z)} + E_\Omega(z)e^{i(\Omega t - k_\Omega z)} \\ &\qquad + E_1(z)e^{i(\omega_1 t - k_1 z)} + c.c.\Big]. \qquad (2)\end{aligned}$$

From Maxwell's equations and using the small-signal approximation and the parabolic approximation [19], the coupling equations between ω_1 and Ω waves are:

$$\begin{cases}\dfrac{\partial}{\partial z}E_\Omega(z) = \dfrac{i}{2}\left[\dfrac{\mu_0\Omega^2\Delta\varepsilon_\Omega(z)}{k_\Omega}\right]E_\Omega(z) \\ \quad -i\,\dfrac{\mu_0\Omega^2}{k_\Omega}\,d(z)E_0E_1^*(z)e^{i(-\Delta kz)} \\ \dfrac{\partial}{\partial z}E_1(z) = \dfrac{i}{2}\left[\dfrac{\mu_0\omega_1^2\Delta\varepsilon_{\omega_1}(z)}{k_1}\right]E_1(z) \\ \quad -i\,\dfrac{\mu_0\omega_1^2}{k_1}\,d(z)E_0E_\Omega^*(z)e^{i(-\Delta kz)}\end{cases} \qquad (3)$$

where $\Delta k = k_0 - k_1 - k_\Omega$ is the wave vector mismatch, $d(z)$ is the nonlinear coefficient, and $\Delta\varepsilon_{\Omega,\omega_1}(z) = \varepsilon_{\Omega,\,\omega_1}(z) -$ is the dielectric constant fluctuation.

The $\Delta\varepsilon_{\Omega,\omega_1}(z)$ on the right-hand side of (3) results in the coupling between the forward wave and the backward wave. Since only the forward wave is considered, here the above equations are not precise and are difficult to solve. However, in a 1-D photonic crystal, the reflection of the forward wave becomes the backward wave and reduces the intensity of the forward wave. The decrease is not severe if the sample length is short or if the fluctuation of the dielectric constant is small. Besides the intensity decreasing, another influence on the forward wave is the phase change due to the reflection of the backward wave. This is a kind of cascade reflection of the forward wave that may also interfere with the original forward wave and then influence the dispersion relation. To simplify the analysis, we neglect the first items on the right side of (3), but consider the action of a periodic dielectric constant by using the dispersion relation of the 1-D photonic crystal instead of the homogeneous medium. In fact, because of the different dispersion relation with respect to a homogeneous medium, the phase velocity, and group velocity will not be equal to those in a homogeneous medium with the average refractive index. One interesting effect is that a light beam with a frequency near the band gap will decrease its group velocity to almost zero, while the phase velocity will not change much. In our case, we will consider the change in the group velocity while assuming that the phase velocity remains fixed at the average phase velocity of the two components in the photonic crystal. Define $\Gamma_\Omega = -i(\mu_0\Omega C/\overline{n}_\Omega)$, $\Gamma_1 = -i(\mu_0\omega_1 C/n_1)$, where $\overline{n}_\Omega$ and $\overline{n}_1$ are the average refractive indices of the microwave and ω_1 waves, respectively. Given these assumption and definitions, we obtain

$$\begin{cases} \frac{\partial}{\partial z} E_\Omega^*(z) = -\Gamma_\Omega d(z) E_0^* E_1(z) e^{i\Delta k z} \\ \frac{\partial}{\partial z} E_1(z) = \Gamma_1 d(z) E_0 E_\Omega^*(z) e^{i(-\Delta k z)} \end{cases} \quad (4)$$

where $d(z)$ could be Fourier expanded as $d(z) = \sum_{m=-\infty}^{\infty} d_m e^{-iG_m z}$. $G_m = m(2\pi/\Lambda)$ is the mth-order reciprocal vector; thus

$$\frac{\partial}{\partial z} E_\Omega^*(z) = \sum_{m=-\infty}^{\infty} -\Gamma_\Omega d_m E_0^* E_1(z) e^{i(\Delta k - G_m)z}. \quad (5)$$

Since $E_\Omega^*(z)$ depends on the integral on the left side of (5), its value is dominated by the mth term of the reciprocal vector G_m, when G_m is close to Δk [11]. Under this condition, we get

$$\frac{\partial}{\partial z} E_\Omega^*(z) = -\Gamma_\Omega d_m E_0^* E_1(z) e^{i(\Delta k - G_m)z}. \quad (6)$$

For the same reason

$$\frac{\partial}{\partial z} E_1(z) = \Gamma_1 d_m E_0 E_\Omega^*(z) e^{-i(\Delta k - G_m)z}. \quad (7)$$

Define $\Delta G = \Delta k - G_m$, $i\Re_\Omega = -\Gamma_\Omega d_m = i(\Omega c/\overline{n}_\Omega)d_m$, and $i\Re_1 = -\Gamma_1 d_m = i(\omega_1 c/\overline{n}_1)d_m$, where c is the light velocity in vacuum, and $\Re_\Omega$ and $\Re_1$ are both positive real numbers.

With these new parameters, the coupling equations are

$$\begin{cases} \frac{\partial}{\partial z} E_\Omega^*(z) = i\Re_\Omega E_0^* E_1(z) e^{i\Delta G z} \\ \frac{\partial}{\partial z} E_1(z) = -i\Re_1 E_0 E_\Omega^*(z) e^{-i\Delta G z}. \end{cases} \quad (8)$$

The corresponding boundary conditions are

$$\begin{cases} E_\Omega(z)|_{z=0} = E_\Omega(0) = 0 \\ E_1(z)|_{z=0} = E_1(0) \\ \left.\frac{\partial E_\Omega^*(z)}{\partial z}\right|_{z=0} = i\Re_\Omega E_0^* E_1(0) \\ \left.\frac{\partial E_1(z)}{\partial z}\right|_{z=0} = -i\Re_1 E_0 E_\Omega^*(0) = 0. \end{cases} \quad (9)$$

These equations can be easily solved to give

$$E_\Omega(z) = -i\frac{1}{q}\Re_\Omega E_0 E_1^*(0) sh(qz) e^{-i(\Delta G/2)z},$$
$$\text{where } q = \sqrt{\Re_\Omega \Re_1 |E_0|^2 - \left(\frac{\Delta G}{2}\right)^2}. \quad (10)$$

Obviously, the amplitude of $E_\Omega(z)$ could be amplified along the light propagation route and a coherent microwaves at the frequency Ω are produced only if $\Delta G = 0$. The condition $\Delta G = 0$ is the prerequisite for efficient microwave generation just as the phase-matching condition in nonlinear optics. If $\Delta G = \Delta k - G_m = 0$, then $(k_0 - k_1)/\Omega = (k_\Omega/\Omega) + (G_m/\Omega)$. Since $(k_0 - k_1)/\Omega = (k_0 - k_1)/(\omega_0 - \omega_1) = 1/v_g$ and $k_\Omega/\Omega = 1/v_{p,\Omega}$, where v_g is the group velocity of the pump light and $v_{p,\Omega}$ is the phase velocity of the microwaves, the velocity matching condition could be given as $1/v_g = 1/v_{p,\Omega} + G_m/\Omega$ or $v_g = \Omega/(k_\Omega + G_m)$, which is the same as our earlier simple physical analysis.

For achieving efficient microwave generation, the velocity-matching condition should be satisfied. The simplest case is in the homogeneous medium, where $G_m = 0$, thus $v_g = v_{p,\Omega}$, which means that the group velocity of the light should be equal to the phase velocity of the generated microwave, but this condition generally cannot be satisfied.

In addition to an ordinary photonic crystal, we can also consider QPM materials. The action of G_m now needs to be considered. In PPLN, assuming the pump light is injected along the a-axis, we have $v_{g,\omega_0} = v_{p,\omega_0}$, (i.e., there is no group velocity dispersion). In this case, $v_{p,\omega_0} = \Omega/(k_\Omega + G_m)$, which means that the reciprocal vector of QPM material can be used to compensate the velocity mismatch as in the QPM SHG. Therefore, PPLN can be used to generate coherent microwaves. In this sense, a QPM material is a special case of a nonlinear photonic crystal. As an example, for generating 100 GHz of microwave radiation from a 1064-nm YAG laser, each domain thickness of PPLN is 508 μm, which can easily be fabricated.

For a nonlinear photonic crystal, the group velocity dispersion induced by the periodic dielectric constant cannot be neglected. Even if we use the zeroth-order reciprocal vector ($G_m = 0$), the velocity could also be matched. From the dispersion relation of the 1-D photonic crystal [20], the reciprocal

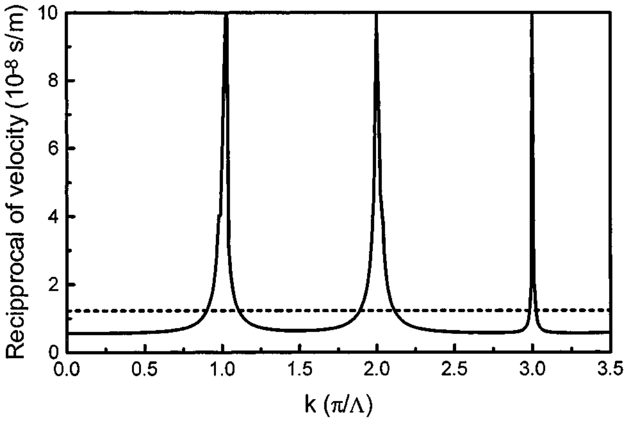

Fig. 2. Velocity matching curves in a $LiNbO_3$/air photonic crystal. Solid line: the reciprocal of the pump light's group velocity as a function of the wave vector. Dashed line: the reciprocal of the phase velocity of the generated 100-GHz microwave. Intersections correspond the matching points.

of the group velocity of a light pulse could be obtained as in the equation shown at the bottom of the next page. When $k = m(2\pi/\Lambda) = G_m$, $1/v_g$ becomes infinite, and the group velocity is zero.

When $m = 0$, the velocity-match condition becomes $v_g = v_{p,\Omega}$. Although the light velocity in a medium is normally much faster than that of a microwave, the group velocity decreases to almost zero near the band gap. Obviously, there should be a region where the velocities could be matched. Fig. 2 shows the reciprocal of the group velocity of a light wave in a photonic crystal that could be fabricated by periodic etching in a $LiNbO_3$ crystal [21]. Each $LiNbO_3$ block has a thickness of 0.5 μm. Neighbor blocks are separated by 0.5 μm. For microwaves with a frequency of 100 GHz, the refractive index of the extraordinary wave in $LiNbO_3$ is 5.11 [22]; thus, the reciprocal of its phase velocity in this sample is 1.23×10^{-8} s/m, which corresponds to the dashed line in Fig. 2. In fact, there are many matching points for producing microwaves in this LN/air photonic crystal. The wavelengths of the pump light should be at 4.122, 2.609, 1.781, 1.399, or 1.064 μm. In general, for generating a specific microwave with a certain frequency from a given pump source, a periodic structure can surely be designed. In addition, besides the group velocity dispersion, the periodic nonlinear optical coefficient in a nonlinear photonic crystal also makes it possible to compensate for the velocity mismatch by the reciprocal vector. In fact, both velocity-matching effects could be utilized simultaneously. We could draw another line in Fig. 2 with the height of $1/v_{p,\Omega} + G_m/\Omega$. Obviously, it should also intersect the curve of $1/v_g$ at many points, giving us more flexibility for pump-light selection. In this case, the matching frequencies are all near the edge of stopband. The pump light is highly reflective and it cannot penetrate the photonic crystal. A big advantage of this scheme is the possibility making the pump light resonant to enhance the nonlinear effects [9]. Since the periodic structure formed a high-Q-value resonant cavity for the pump light, the pumping light intensity is very high in the photonic crystal, thereby increasing the nonlinear frequency conversion. The pump light can be coupled into the crystal through a well-designed defect or the pump light itself can be generated inside the photonic crystal through a nonlinear or laser process. For example, this is possible if the photonic crystal contains some active rare earth ions that can self-generate the pump light. This important application of a photonic crystal is now an intense topic of study [3], [4]. The higher the reflection ratio of the pump light, the lower the pumping threshold. A compact coherent wave source thus may be constructed based on this idea. As for the most achievable conversion efficiency of coherent microwave generation in a nonlinear photonic crystal, the photon conversion efficiency can reach 100% in theory, which means that each pump photon is split into one microwave photon and another photon with a slightly lower light frequency. However, since the microwave frequency is much lower than the pump frequency and the photon energy is correspondingly proportional to the frequency, the microwave power should be much lower than the pump light power even if they contain the same number of photons. The most achievable conversion efficiency is Ω/ω_0. Lower pump light frequency and higher microwave frequency corresponds to higher power conversion. For example, for generating terahertz radiation from 1.55-μm pump light, the efficiency can be 1%, while generating microwaves at 500 GHz from the 1.55-μm light would have an efficiency smaller than 0.25%. For getting a 1-mW coherent microwave, the pump light should at least have the power of several hundred milliwatts. Such power levels are easily achievable today.

In the example above, besides the group velocity dispersion, the reciprocal vectors of a photonic crystal could also be used to compensate for the velocity mismatch, just like the QPM. Utilizing these two effects together in a nonlinear photonic crystal is possible and may induce novel properties, especially near the band gap or a defect mode [3], [6]. Comparing the structures and physical properties of photonic crystals and QPM material, we can treat the photonic crystal as such a general concept that QPM material is a kind of special photonic crystal.

III. Summary

In summary, we have proposed the physical mechanism in which a novel coherent microwave source in a nonlinear photonic crystal through the optical rectification. Compared with traditional electron-beam-induced microwaves, our all-solid design is economical, compact, and stable. We have shown that both the reciprocal vectors due to the periodic nonlinear coefficient and the group velocity dispersion induced by the periodic

$$\frac{1}{v_g} = \frac{\sin\frac{n_a a\omega}{c}\cos\frac{n_b b\omega}{c}\left[n_a a + \frac{1}{2}\left(\frac{n_b}{n_a}+\frac{n_a}{n_b}\right)n_b b\right] + \cos\frac{n_a a\omega}{c}\sin\frac{n_b b\omega}{c}\left[n_b b + \frac{1}{2}\left(\frac{n_b}{n_a}+\frac{n_a}{n_b}\right)n_a a\right]}{\Lambda C\sin(k\Lambda)}$$

dielectric constant could be used to compensate for the velocity mismatch between the generated microwave and the pump light.

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