Observation of continuous-wave second-harmonic generation in semiconductor waveguide directional couplers

Po Dong, Jeremy Upham, Aju Jugessur and Andrew G. Kirk

Photonic Systems Group, Department of Electrical and Computer Engineering, McGill University, 3480 University St, Montreal, QC, H3A 2A7, Canada
andrew.kirk@mcgill.ca

Abstract: We report the observation of continuous-wave second-harmonic generation in waveguide directional couplers. We employ a GaAs/AlGaAs system and observe four resonance peaks in a ~15nm spectral range, with a maximal conversion efficiency of $1.6\%W^{-1}cm^{-2}$. This observation is theoretically explained by the coupled-mode theory. This new configuration has the potential to open a new range of applications for nonlinear frequency conversion.

OCIS codes: (190.2620) Frequency conversion; (130.4310) Nonlinear integrated optics; (190.4360) Nonlinear optics, devices; (190.5970) Semiconductor nonlinear optics

---

References and Links

1. R. W. Boyd, *Nonlinear Optics* (Academic Press Inc., 2003).
2. M. M. Fejer, "Nonlinear optical frequency conversion," Phys. Today **47**, 25-31 (1994).
3. J. P. Van der Ziel, "Phase–matched harmonic generation in a laminar structure with wave propagation in the plane of the layers," Appl. Phys. Lett. **26**, 60-61 (1975).
4. A. Fiore, V. Berger, E. Rosencher, P. Bravetti, and J. Nagle, "Phase matching using an isotropic nonlinear optical material," Nature **391**, 463-465 (1998).
5. J. A. Armstrong, N. Bloembergen, J. Ducuing, and P. S. Pershan, "Interactions between light waves in a nonlinear dielectric," Phys. Rev. **127**, 1918-1939 (1962).
6. V. Berger, "Nonlinear photonic crystals," Phys. Rev. Lett. **81**, 4136-4139 (1998).
7. M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, "Quasi-phase-matched second harmonic generation–tuning and tolerance," IEEE J. Quantum Electron. **28**, 2631-2654 (1992).
8. G. L. J. A. Rikken, C. J. E. Seppen, E. G. J. Staring, and A. H. J. Venhuizen, "Efficient modal dispersion phase-matched frequency-doubling in poled polymer waveguides," Appl. Phys. Lett. **62**, 2483-2485 (1993).
9. P. K. Tien, R. Ulrich, and R. J. Martin, "Optical second harmonic generation in form of coherent Cerenkov radiation from a thin-film waveguide," Appl. Phys. Lett. **17**, 447-449 (1970).
10. P. Dong, and A. G. Kirk, "Nonlinear frequency conversion in waveguide directional couplers," Phys. Rev. Lett. **93,** 133901 (2004).
11. S. J. B. Yoo, C. Caneau, R. Bhat, M. A. Koza, A. Rajhel, and N. Antoniades, "Wavelength conversion by difference frequency generation in AlGaAs waveguides with periodic domain inversion achieved by wafer bonding," Appl. Phys. Lett. **68**, 2609-2611 (1996).
12. T. Skauli, "Measurement of the nonlinear coefficient of orientation-patterned GaAs and demonstration of highly efficient second-harmonic generation," Opt. Lett. **27**, 628-630 (2002).
13. K. Moutzouris, S. V. Rao, M. Ebrahimzadeh, A. De Rossi, M. Calligaro, V. Ortiz, and V. Berger, "Second-harmonic generation through optimized modal phase matching in semiconductor waveguides," Appl. Phys. Lett. **83**, 620-622 (2003).
14. S. Ducci, L. Lanco, V. Berger, A. De Rossi, V. Ortiz, and M. Calligaro, "Continuous-wave second harmonic generation in modal phase matched semiconductor waveguides," Appl. Phys. Lett. **84**, 2974-2976 (2004).
15. A.Yariv, *Optical Electronics in Modern Communications* (Oxford University Press, 1997).
16. A. A. Maier, "Coupled modes phase matching and synchronous non-linear wave interaction in coupled waveguides," Kvantovaya Elektronika **7**, 1596-1598 (1980).
17. S. I. Bozhevol'nyi, K. S. Buritskii, E. M. Zolotov, and V. Chernykh, Sov. Tech. Phys. Lett. **7**, 278 (1981).
18. X. G. Huang and M. R. Wang, "A novel quasi-phase-matching frequency doubling technique," Opt. Commun. **150**, 235-238 (1998).

#10343 - $15.00 USD Received 17 January 2006; revised 14 March 2006; accepted 14 March 2006

19. G. Assanto, G. Stegeman, M. Sheik-Bahae, and E. V. Stryland, "All-optical switching devices based on large nonlinear phase shifts from second harmonic generation," Appl. Phys. Lett., **62**, 1323-1325 (1993).
20. R. Iwanow, R. Schiek, G. I. Stegeman, T. Pertsch, F. Lederer, Y. Min, and W. Sohler, "Observation of discrete quadratic solitons", Phys. Rev. Lett. **93**, 113902 (2004).
21. Chowdhury, and L. McCaughan, "Continuously phase-matched M-waveguides for second-order nonlinear upconversion," IEEE Photon. Technol. Lett. **12**, 486-488 (2000).
22. T. Reed, and A. P. Knights, *Silicon photonics* (John Wiley & Sons Inc., 2004).
23. K. Ekert, J. G. Rarity, P. R. Tapster, and G. M. Palma, "Practical quantum cryptography based on 2-photon interferometry," Phys. Rev. Lett. **69**, 1293-1296 (1992).
24. D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, "Experimental quantum teleportation," Nature, **390**, 575-579 (1997).

1. Introduction

Nonlinear-optical frequency conversion generates coherent radiation at frequencies where lasers are not convenient. Efficient frequency conversion requires a phase-matching condition to compensate for material dispersion [1]. Phase matching can be achieved by exploiting the birefringence exhibited in anisotropic crystals [2] or artificial structures [3-4]. Quasi-phase-matching utilizes spatially periodic modulation of nonlinear coefficients and has achieved great success due to its versatility in material and pump frequency [5-7]. Other phase-matching methods, such as modal-dispersion [8] and Cerenkov phase matching [9], have been achieved in single-waveguide structures. In this paper, we experimentally demonstrate second harmonic generation in directional couplers (two coupled waveguides) [10], rather than bulk crystals or single waveguides. The experimental demonstration is based on a GaAs/AlGaAs material system which has attracted much attention as a nonlinear material in recent years due to its large nonlinear constants, mature epitaxial fabrication process, and ease of incorporation into diode lasers [4, 11-14]. The demonstrated structure opens the way to realize semiconductor laser sources by incorporating the directional couplers with diode lasers. Such devices can find applications in spectroscopic systems, telecommunication networks, and quantum computation.

Waveguide directional couplers consist of two closely spaced waveguides. Light intensity modulates periodically between the two waveguides as a function of distance [15]. The oscillation behavior of directional couplers can be explained by the propagation of multiple supermodes in compound structures. Second harmonic generation in such structures was first demonstrated and explained in the context of phase matching between supermodes [16-17]. In Refs. [10] and [18], the phenomenon was investigated in the frame of coupled-mode theory and the results were interpreted by quasi-phase matching [18] and resonance between the coupling coefficients of directional couplers and the phase mismatch [10]. These explanations are certainly equivalent. However, the advantage of using the coupled-mode theory is that it considers all possible conversion processes in a single set of equations. This makes it more accurate when the resonance wavelengths for different conversion processes are close, under which condition different conversion processes may influence each other. In this configuration, the resonance can be understood by the following descriptions. Because the power in each of the two waveguides can oscillate with the propagation length, the directional coupler acts as a harmonic oscillator for the optical wave. The nonlinear polarization P at the frequency of the generated wave has the form $P \propto \exp(i\Delta kz)$, where Δk is the phase mismatch and z is the propagation length. The nonlinear polarization is analogous to an external harmonic force applied on the harmonic oscillator. As is well known, a harmonic oscillator driven by an external harmonic force at resonance obtains the largest magnitude of oscillation. A similar resonance phenomenon appears here, and it was shown that the resonance condition is equivalent to the phase-matching condition [10]. It is to be noted that second harmonic generation (SHG) in directional couplers has also been investigated for the purposes of optical switching [19] and soliton generation [20].

2. Design of experiment

We implemented a directional coupler as an epitaxially grown dual-core channel waveguide on <1, 0, 0> GaAs substrates. The designed epitaxial structure is 1500nm $Al_{0.9}Ga_{0.1}As$ / 140nm $Al_{0.3}Ga_{0.7}As$ / 300nm $Al_{0.5}Ga_{0.5}As$ / 140nm $Al_{0.3}Ga_{0.7}As$ / 500nm $Al_{0.9}Ga_{0.1}As$ / 140nm $Al_{0.3}Ga_{0.7}As$ / 300nm $Al_{0.5}Ga_{0.5}As$ / 140nm $Al_{0.3}Ga_{0.7}As$ / 1500nm $Al_{0.9}Ga_{0.1}As$. The $Al_{0.9}Ga_{0.1}As$ layers serve as cladding and as the separating layer between the two waveguides. The $Al_{0.3}Ga_{0.7}As/Al_{0.5}Ga_{0.5}As/Al_{0.3}Ga_{0.7}As$ combination acts as the guiding layer and this is a type of "M" waveguide designed for optimizing the field overlap between TE_2 mode at the second-harmonic frequency and TE_0 and TM_0 modes at the fundamental frequencies [21]. A typical refractive index distribution and intensities for these modes are plotted in Fig. 1.

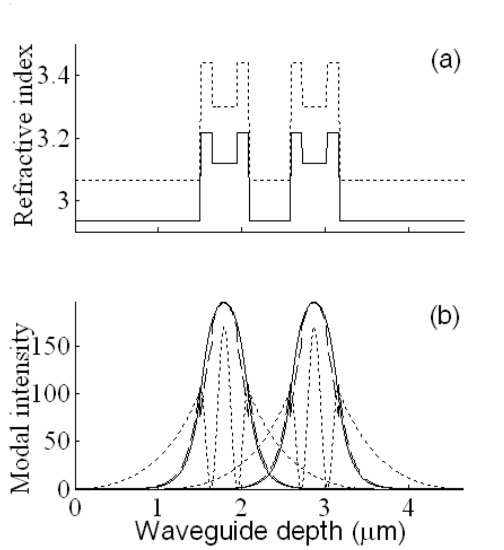

Fig. 1. (a) Refractive index distribution at 1.55μm (solid line) and 0.775μm (dotted line). (b) Intensity distribution $|E|^2$ of modes TE_0 (solid line) and TM_0 (dashed line) at 1.55μm, and TE_2 at 0.775μm (dotted line).

Using $A_{\omega_j}(z)$ and $B_{\omega_j}(z)$ to represent the slowly varying amplitudes in waveguides 1 and 2, respectively, the coupled wave equations are

$$\begin{aligned} \frac{dA_{2\omega}^{TE_2}}{dz} &= -i\kappa_{2\omega}^{TE_2} B_{2\omega}^{TE_2} - i\eta A_{\omega}^{TE_0} A_{\omega}^{TM_0} \exp(i\Delta kz) \\ \frac{dB_{2\omega}^{TE_2}}{dz} &= -i\kappa_{2\omega}^{TE_2} A_{2\omega}^{TE_2} - i\eta B_{\omega}^{TE_0} B_{\omega}^{TM_0} \exp(i\Delta kz) \end{aligned} \tag{1}$$

Here, $\kappa_{2\omega}^{TE_2}$ is the mode-coupling coefficient of the directional coupler for the second harmonic [15], η includes the product of the nonlinear optical coefficient and the overlap integral of the fundamental and the second harmonic waves, and $\Delta k = k_{2\omega}^{TE_2} - k_{\omega}^{TE_0} - k_{2\omega}^{TM_0}$ is the phase mismatch (k is the wave number). The mode-coupling coefficients indicate how rapidly the power in the first waveguide is transferred to the second waveguide. The first terms in the right-hand sides of the above equations describe the coupling effect of the directional coupler and the second terms in the right-hand sides result from the nonlinear effects. Under the non-depletion assumption which implies that the presence of the second harmonic does not influence the motion of the fundamental wave, the amplitudes for the fundamental wave oscillate between the two waveguides:

#10343 - \$15.00 USD Received 17 January 2006; revised 14 March 2006; accepted 14 March 2006

$$
\begin{aligned}
A_{\omega}^{TE_0} &= c_1 \exp\left(i\kappa_{\omega}^{TE_0} z\right) + c_2 \exp\left(-i\kappa_{\omega}^{TE_0} z\right) \\
B_{\omega}^{TE_0} &= -c_1 \exp\left(i\kappa_{\omega}^{TE_0} z\right) + c_2 \exp\left(-i\kappa_{\omega}^{TE_0} z\right) \\
A_{\omega}^{TM_0} &= c_1 \exp\left(i\kappa_{\omega}^{TM_0} z\right) + c_2 \exp\left(-i\kappa_{\omega}^{TM_0} z\right) \\
B_{\omega}^{TM_0} &= -c_1 \exp\left(i\kappa_{\omega}^{TM_0} z\right) + c_2 \exp\left(-i\kappa_{\omega}^{TM_0} z\right)
\end{aligned}
\tag{2}
$$

where $\kappa_{\omega}^{TE_0}$ and $\kappa_{\omega}^{TM_0}$ are the coupling coefficients of TE_0 and TM_0 modes at the fundamental frequency, c_1 and c_2 are two constants depending on how much power is coupled into the individual waveguides from free space. In our experiment, we align the input polarization of the fundamental wave at 45 degrees with respect to the waveguide y-direction, by which the input power is divided equally in TE mode and TM mode. Because the modal fields for TE_0 and TM_0 do not differ very much, it is reasonable to assume that the power ratio coupled in the first to the second waveguide are identical for TE_0 and TM_0. This results in identical constants c_1 and c_2 for TE_0 and TM_0 modes.

Substituting Eq. (2) into Eq. (1) results in four resonance conditions at which efficient SHG should be observed

$$
\begin{aligned}
\pm\left(\kappa_{\omega}^{TE_0} + \kappa_{\omega}^{TM_0}\right) + \Delta k &= -\kappa_{2\omega}^{TE_2} \\
\pm\left(\kappa_{\omega}^{TE_0} - \kappa_{\omega}^{TM_0}\right) + \Delta k &= \kappa_{2\omega}^{TE_2}
\end{aligned}
\tag{3}
$$

The above conditions, if expressed by modal-matching configuration, can be interpreted by phase matching among TE supermodes and TM supermodes of the fundamental wave, and TE supermodes of the second harmonic wave. Since the supermodes appear in pairs, there are eight combinations of these conversions. Considering the symmetry requirement, however, the number is reduced to four, which corresponds to the number of resonance conditions in Eq. (3). One can easily, following the definition of the supermodes, find the corresponding matching conversion processes in the language of supermodes. However, we have stressed that the advantage of using the coupled-mode theory is that it considers all possible conversion processes. In our case, the four resonance conditions in Eq. (3) are derived directly by the coupled equations of Eq. (2).

#10343 - $15.00 USD Received 17 January 2006; revised 14 March 2006; accepted 14 March 2006

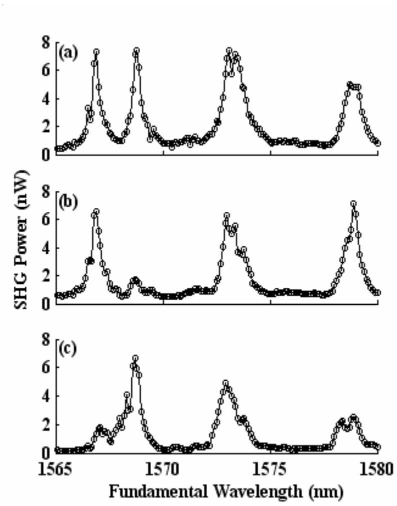

Fig. 2. Typical SHG power as a function of the fundamental wavelength. Three curves were obtained by varying the position of input beam. It is evident that four resonance peaks are found, and the relative peak ratio at resonance can be alternated by the change of input location.

3. Experimental results and discussions

In the experimental implementation, ridge structures, oriented along the <0, 1, 1> direction and of width 5 µm, were dry etched in order to provide two-dimensional confinement. The tested directional coupler has a length of 4 mm. Since the optical power oscillates in between two guiding layers, it is difficult to precisely measure the waveguide loss. However, with a Fabry-Perot technique [22], we approximately obtained the loss figure as ~1.24cm^{-1} for TE input and ~2.71 cm^{-1} for TM input, both at a 1550nm wavelength. We were unable to measure the waveguide loss of the TE_2 mode at the second-harmonic frequency.

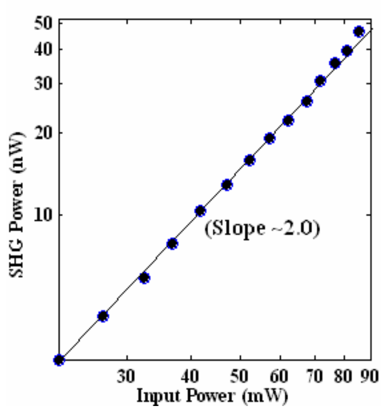

Fig. 3. Log-log plot of the second-harmonic output power as a function of the input fundamental power. The best fit gives a slope ~2.0 which verifies the quadratic dependence of the SHG on the pumping power.

For the optical measurement, a continuous-wave laser, tunable from 1.5 to 1.6 µm and then amplified by an erbium-doped fiber amplifier, was coupled into the waveguide via a 40X objective lens. The input has a spectral FWHM of ~0.05nm, measured by a spectrum analyzer. A second 40X objective was used to collect the transmitted fundamental wave and the SHG signal. A typical set of spectra is shown in Fig. 2, which explicitly demonstrates four SHG peaks in the spectral range from 1.565 to 1.580 µm. The resonance take place at, 1.5668, 1.5686, 1.5730 and 1.5790 µm, and the FWHM spectral widths are ~0.4, ~0.45, ~1.1, and ~1.1nm, respectively. The SHG polarization was measured by a standard polarizer. The dependence of SHG power on the input polarizations was carefully inspected and we concluded that all the four resonances correspond to TE + TM input and TE output. The appearance of four resonance peaks uniquely verifies the theory proposed in Ref. [10]. The spectral widths of the signal are consistent with those reported in similar structures, but for single waveguides [13-14]. However, it is difficult to precisely predict, from simulation, the exact peak locations because of the lack of the knowledge of the exact refractive index distribution and feature sizes. For example, using a two-dimensional simulation of the directional coupler, the expected resonance peaks should appear between 1.54 to 1.55 µm, which are about 20 nm away from the experimental results (this deviation between experiment and design exists in similar GaAs/AlGaAs structures [13-14] and other waveguide systems [8]). Nevertheless, we expect that the first to the fourth peaks may correspond to resonance conditions $-\left(\kappa_{\omega}^{TE_0}+\kappa_{\omega}^{TM_0}\right)+\Delta k=-\kappa_{2\omega}^{TE_2}$, $\left(\kappa_{\omega}^{TE_0}-\kappa_{\omega}^{TM_0}\right)+\Delta k=\kappa_{2\omega}^{TE_2}$, $-\left(\kappa_{\omega}^{TE_0}-\kappa_{\omega}^{TM_0}\right)+\Delta k=\kappa_{2\omega}^{TE_2}$ and $\left(\kappa_{\omega}^{TE_0}+\kappa_{\omega}^{TM_0}\right)+\Delta k=-\kappa_{2\omega}^{TE_2}$, respectively. At the first resonance, for example, the coupling coefficients are calculated as ~0.04 μm^{-1} for TE_0 and TM_0 pump and ~0.02 μm^{-1} for TE_2 SHG, which implies that the power of the fundamental wave exchanges between the two waveguides about one hundred times. The relative peak values of the four resonances can be changed by modifying the position of input beam, as shown in Fig. 2, where the three curves were obtained with different locations of input beam. This occurs because variation of the input position modifies the power ratio coupled into the first and the second waveguide, and therefore modifies the value of c_1 and c_2 in Eq. (2). This imprecision could be avoided in future by the fabrication of a more complex waveguide device with a single input waveguide connected to the coupled waveguides with a controlled splitting ratio. By optimizing the 1573nm resonance, we achieved a maximum measured SHG power of 50nW with a 90mW input power. The SHG power as a function of input power was then measured and plotted in Fig. 3. The fitting to the slope results in a value of 2.0 on a log-log plot. This confirms the quadratic dependence of the SHG power on the pumping power. By measuring the transmitted power of the fundamental wave, we estimated that the average internal pumping power for the TE and TM is $P_{TE}\approx 5mW$ and $P_{TM}\approx 5mW$. After taking into account the numerical aperture of the collecting lens (0.65) and the facet reflectivity for the second harmonic (0.6), we estimate that only 20% of the generated SHG was collected [14]. The normalized conversion efficiency is calculated to be $\eta = P_{SHG}/\left(4P_{TE}P_{TM}L^2\right) = \sim 1.6\%\ W^{-1}\ cm^{-2}$ (for a detailed analysis of this estimation, we refer to Ref. [14]). Several factors may explain the low SHG power obtained. The coupling efficiency to the directional coupler is only ~10% because of the loss from the input objective, the input facet reflectivity and the mode-matching factor. Furthermore, the loss of the TE_2 mode at the second harmonic frequency is expected to be very high, which limits the effective conversion length. Another reason is that the pump power is distributed into the two waveguides, which actually reduce the effective power in each individual waveguide. Further optimization, therefore, can include improving the coupling efficiency, reducing the leaky loss of SHG mode, optimizing the modal overlap between the fundamental wave and SHG, and choosing an appropriate interaction length.

#10343 - $15.00 USD Received 17 January 2006; revised 14 March 2006; accepted 14 March 2006

4. Conclusion

The GaAs/AlGaAs directional coupler that we have demonstrated here has application not only for the SHG process, but also for difference-frequency generation. By incorporating directional couplers in/out of the cavity of quantum-well lasers, tunable compact sources which emit light at around 750nm can be produced. Based on the unique properties of multi-resonance within a small spectral range, multiple wavelength outputs can be generated by a single pulsed pump. Such light sources may be very useful in many areas where two or more lasers are needed, such as optical metrology, optical switching, and four-wave mixing. Furthermore, the directional coupler is intrinsically a two-port device which may be suited to construct two-photon optical parametric down-conversion. Such devices can generate entangled pairs of photons which can find applications in quantum optics experiments, from quantum cryptography and teleportation to the Bell experiment [23-24]. The proposed configuration has potential for application in any suitable material system and is not restricted to GaAs/AlGaAs. Directional couplers have very modest fabrication requirements when compared to quasi-phase matching techniques and potentially open the way to a much broader application of nonlinear optical processes across a much wider range of wavelengths.

In summary, we have experimentally demonstrated continuous-wave SHG in Ga/AlGaAs directional couplers. To our knowledge, this is the first experimental proof of frequency conversion in semiconductor directional couplers. We show that four resonance peaks appear in a 15nm spectral range and η=~1.6%$W^{-1}cm^{-2}$ is obtained experimentally. To our knowledge, this phenomenon has not been shown in bulk materials or single waveguides.

This work was supported by the Natural Science and Engineering Research Council of Canada. We would like to thank N. Bélanger and Dr. J. Laniel for helpful discussions and comments on experiments, V. Logiudice, N. Lemaire, D. W. Berry, R. Gagnon at McGill University, and H. Lee at Toronto University for assistance with waveguide fabrication.