Four-Wave Mixing Wavelength Conversion Efficiency in Semiconductor Traveling-Wave Amplifiers Measured to 65 nm of Wavelength Shift

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Abstract—**The efficiency of broadband optical wavelength conversion by four-wave mixing in semiconductor traveling-wave amplifiers is measured for wavelength shifts up to 65 nm using a tandem amplifier geometry. A quantity we call the relative conversion efficiency function, which determines the strength of the four-wave mixing nonlinearity, was extracted from the data. Using this quantity, gain requirements for lossless four-wave mixing wavelength conversion are calculated and discussed. Signal to background noise ratio is also measured and discussed in this study.**

I. Introduction

WAVELENGTH conversion is recognized as an important function in future broadband multichannel lightwave systems, since it makes possible many other useful system functions such as wavelength reuse and dynamic wavelength routing and switching. Demonstrations to date of wavelength converters include: optical triggering in DFB lasers with saturable absorbers [1]; gain saturation in semiconductor optical amplifiers [2] and lasers [3]; difference frequency generation in $LiNbO_3$ channel waveguides [6]; and four-wave mixing (FWM) in dispersion-shifted fibers [4], semiconductor lasers [5] and traveling wave amplifiers (TWA's) [7], [8]. Various limitations with respect to tuning and modulation format are inherent with most of these wavelength conversion techniques. However, wavelength conversion based on FWM in semiconductor TWA's allows continuous tuning of input and output wavelengths over the entire amplifier gain bandwidth, and the process is also transparent to the modulation format of the data.

Highly nondegenerate FWM in semiconductor lasers and amplifiers was first proposed and analyzed by Agrawal [9]. Since the time of that work, measurements of FWM in semiconductor TWA's have been used as a spectroscopic tool to study ultrafast intraband dynamics [10]–[12]. Only recently has the idea of using FWM in TWA's to translate optical carriers from one wavelength to another (*i.e.*, wavelength conversion) been proposed and demonstrated. In particular, wavelength conversion of 622 Mb/s data over 20 nm has recently been demonstrated using FWM in TWA's [7] and the conversion efficiency has been characterized for wavelength shifts up to 27 nm [8]. In this paper we present new results showing conversion over wavelength spans as large as 65 nm. We use this data to extract the wavelength-shift dependence of a quantity we call the relative conversion efficiency function, which gives the strength of the FWM nonlinearity in the TWA. Using this quantity, we calculate and discuss TWA gain requirements for lossless FWM wavelength conversion. We also observe experimentally that wavelength conversion efficiency varies as the cube of TWA single-pass gain. In addition, we discuss and measure the signal to background noise ratio.

In the course of our previous work [8], we have shown that the theoretical efficiency of TWA FWM wavelength conversion can be expressed by the simple relation:

$$\eta = 3G + 2I_p + R(\Delta\lambda) \tag{1}$$

where η is the ratio in dB of the converted signal output power to the signal input power and G is the saturated TWA optical gain. A crucial point is the presence of $3G$ in this expression. This occurs because the nonlinear field mixing involved in the FWM process uses the pump wave twice and the input signal once so that overall the amplifier's single-pass gain acts three times. (As an aside, we note that $3G$ in (1) assumes equal gain for pump and signal waves. In general, we have $2G_p + G_q$ where G_p and G_q are pump and input signal gains, respectively.)

Other parameters appearing in (1) include the input optical pump-wave power I_p (expressed in dBm), and a quantity we call the relative efficiency function, $R(\Delta\lambda)$, which is given by [8],

$$R(\Delta\lambda) = 20\log\left|\sum_{m=1}^{3} c_m \cdot \frac{1}{1 - i2\pi f\tau_m}\right| \tag{2}$$

where the three terms in the summation represent contributions to FWM wavelength conversion from the three responsible mechanisms: carrier density modulation, dynamic carrier heating and spectral hole burning. $\Delta\lambda$ is the wavelength shift and f is the detuning frequency, defined as the difference between the optical frequencies of the pump and input signal waves;

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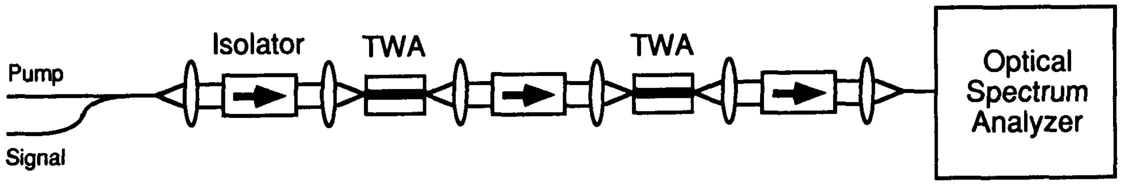

Fig. 1. FWM wavelength conversion setup showing a tandem amplifier geometry.

f is related to the wavelength shift by $f = -\frac{c}{2\lambda^2} \cdot \Delta\lambda$. In addition, $\{\tau_m\}$ are the lifetimes associated with the various contributing FWM mechanisms and $\{c_m\}$ are complex coupling coefficients giving the strengths of the three contributing FWM mechanisms. Derivation of (1)–(2) can be found in [8].

The cubic dependence on gain in (1) indicates that a high TWA gain is critical for efficient broadband wavelength conversion. In this measurement, we employed a novel tandem-amplifier geometry in which two 1.5 μm tensile-strained InGaAs/InGaAsP MQW TWA's [13], separated by an optical isolator, were replaced in series as shown in Fig. 1. The tandem amplifier provided much higher gain (small-signal gain of about 30 dB) and thus improved conversion efficiency significantly, thereby extending the measurable wavelength conversion range.

Two, single-frequency, tunable, Er-doped fiber ring lasers [14] were used as pump and input signal source in the measurement. The converted signals and the wavelength shifts were measured using an HP 70950A optical spectrum analyzer. We first measured the dependence of the conversion efficiency η on the saturated single-pass TWA gain G. For this measurement, wavelengths and powers of the pump and signal waves remained fixed, and the single-pass gain was varied by changing the bias currents of the two TWA's between 80 mA and 175 mA. Shown in Fig. 2 is typical conversion efficiency data plotted versus single-pass saturated optical gain. Conversion was measured from 1532.0 nm to 1523.0 nm with a pump power of -5.2 dBm and an input signal power of -11.3 dBm. Over this wavelength span, G has negligible wavelength dependence. The measured slope of 3.18 verified the cubic dependence of efficiency on single-pass gain. Similar values for the slope were obtained for many other wavelength shifts and input power levels.

The wavelength-shift dependence of the conversion process was also measured using the setup shown in Fig. 1 for both wavelength up- and down-conversion. In the down-conversion experiment, the pump was fixed at 1526.0 nm with -5.3 dBm of power coupled into the TWA wavelength converter. The input signal power varied as the fiber laser source was tuned and was typically in the range of -11.0 dBm to -8.0 dBm. The maximum wavelength down-shift measured in this study was as large as 65 nm, corresponding to a frequency shift of 8 THz. In the up-conversion measurement, the pump was fixed at 1549.0 nm with a power of -6.0 dBm, and the input signal was in the range of -12.0 to -9.0 dBm. Wavelength up-conversion was measured for shifts up to 47.5 nm, corresponding to a frequency shift of -6 T hz. The measurement of wavelength conversion up to 65 nm, which is the largest wavelength shift demonstrated to date using FWM in TWA's, shows that ultrafast FWM dynamics in semiconductor TWA's are capable of generating converted signals over very large wavelength spans.

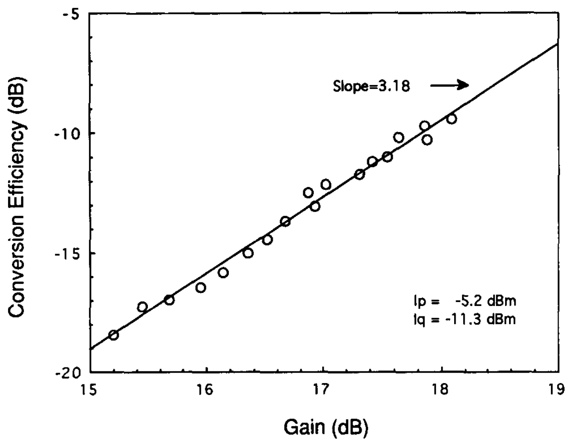

Fig. 2. Measured conversion efficiency η versus saturated single-pass TWA optical gain, showing cubic dependence of efficiency on gain.

The conversion efficiency η for both positive and negative wavelength shifts is presented in Fig. 3, where the efficiency is normalized using the typical parameter values in this study: pump power of -5.5 dBm, signal power of -10 dBm and saturated optical gain G of 18.2 dB (corresponding to the total input power). The normalization may introduce a small, but negligible error arising from slight spectral variation in the saturated TWA gain for the pump and input signal over the wavelength spans measured. As shown in Fig. 3, good conversion efficiencies were achieved with a modest pump power of -5.5 dBm (for example, -12.3 dB for -10 nm conversion). An efficiency asymmetry with respect to positive and negative wavelength shifts, and an overall higher conversion efficiency for wavelength down-conversion can also be seen in the data. These features, which are similar to the results of our previous study [12], are caused by phase interferences which occur between the various contributing inter- and intraband FWM mechanisms.

Also show in Fig. 3 is the relative conversion efficiency function $R(\Delta\lambda)$ extracted using (2) from the data of measured conversion efficiency η. The relative conversion efficiency function, as shown in (2), involves only parameters such as saturation powers and relaxation time constants associated with various inter-and intraband FWM mechanisms. Under conditions of strong gain saturation, we would expect $R(\Delta\lambda)$

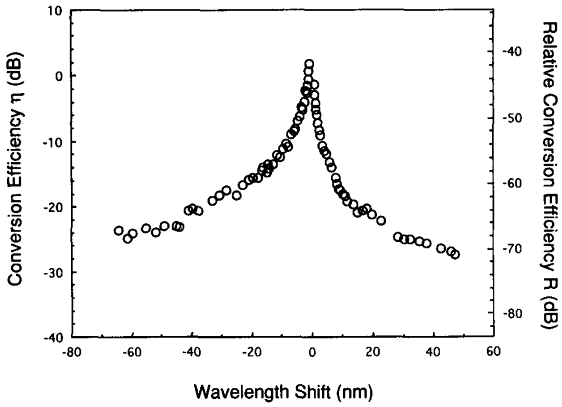

Fig. 3. Measured conversion efficiency η and relative conversion efficiency function $R(\Delta\lambda)$ versus wavelength shift.

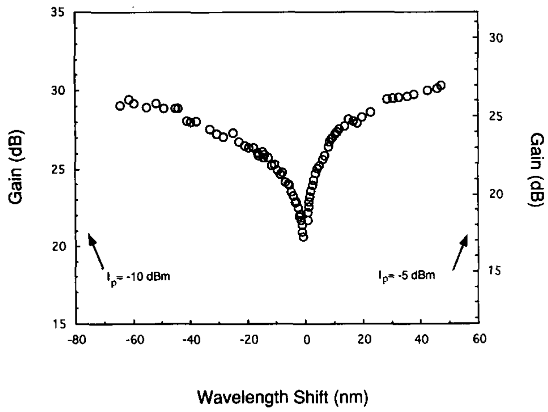

Fig. 4. Single-pass TWA optical gain required for lossless wavelength conversion for $I_p = -10$ dBm (labels on the left side), and $I_p = -5.0$ dBm (labels on the right side).

to depend on input power and TWA drive current. However, the variation of $R(\Delta\lambda)$ for a wide range of bias current (80 mA to 175 mA) and input power(-10 dBm to -0.7 dBm) was found in this study to be insignificant, presumably owing to the large TWA saturation powers. The measurement of $R(\Delta\lambda)$ up to 65 nm in this measurement thus not only extends our understanding of the fundamental nonlinear processes in TWA's, but also makes it possible to establish the requirements on other quantities in (1) for realization of specific conversion efficiencies. This is of obvious practical importance since the attainable conversion efficiency will be a key parameter for system applications.

Based on the measured $R(\Delta\lambda)$, the TWA single-pass gain required for lossless wavelength conversion was calculated for FWM pump powers of -10 and -5.0 dBm. The calculated gain requirements are plotted versus the desired wavelength shift in Fig. 4. Because of the cubic gain dependence, it can be seen that 100% efficiency is attainable for wavelength shifts as large as 65 nm with saturated TWA gains in the range of 30 dB.

Finally, the ratio of converted signal to amplified spontaneous emission (ASE) noise (SNR) is another important

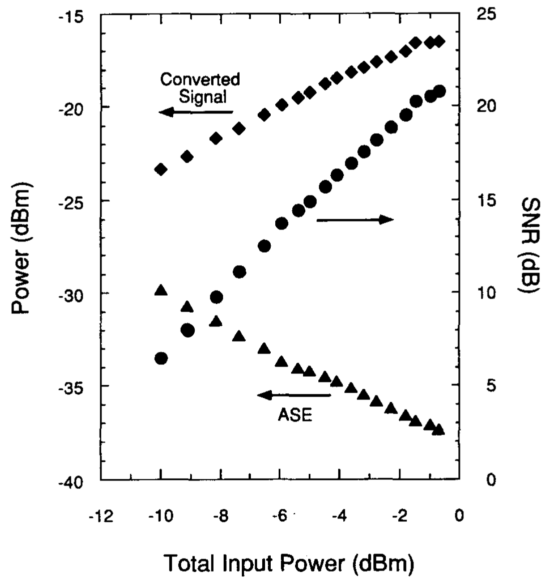

Fig. 5. Measured converted signal power, ASE noise (normalized to 0.1 nm bandwidth) and SNR versus total input power.

parameter for a wavelength converter. SNR (ASE noise normalized to a 0.1 nm bandwidth) for a total input power level of -4.2 dBm (as used in Fig. 3) was about 15 dB for -5 nm of shift and steadily dropped to 0 dB slightly beyond -65 nm of shift. However, improvement in the SNR can be expected with higher total input power (pump + input signal) because SNR increases with the total input power. This effect was previously observed in [7] and also observed in this measurement. It results because of ASE reduction in conjunction with increasing converted signal power as the amplifier saturates. The fact that converted signal power continues to increase in this regime is due to its cubic dependence on total output power at a fixed pump to signal power ratio. This can be seen by using (1) to write the converted output signal power (expressed in dBm) in terms of output power as follows,

$$I_{\text{Conv}} = 3I_{\text{Out}} + R(\Delta\lambda) + 10\log\frac{\Gamma}{(1+\Gamma)^3} \tag{3}$$

where Γ is the ratio of amplified input signal to amplified input pump (i.e., approximately the ratio of input signal to input pump power) and where I_{Out} (in dBm) is the total amplified pump power plus the amplified input signal power. Shown in Fig. 5 is measured converted signal power, ASE noise power (normalized 0.1 nm bandwidth), and SNR as a function of total input power for a 5 nm wavelength down shift. The maximum SNR is 20.8 dB for -0.7 dBm of total input power. In addition, using (3), the optimal Γ value for maximum converted power is found to be 0.5.

In summary, we have used a tandem amplifier geometry to measure broadband FWM wavelength conversion efficiency over wavelength spans as large as 65 nm. We have used this data to obtain the relative conversion efficiency function, which gives the strength of intrinsic FWM nonlinearity in the TWA's. We then calculated and discussed the TWA gain requirements for lossless wavelength conversion and found that at moderate pump power levels (-10 to -5 dBm) lossless wavelength conversion is attainable for spans as large as 65 nm with optical gain under 30 dB. Signal to noise ratio was also measured and discussed.

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