Theoretical and experimental investigation on overshoot characteristic of gain-clamped wavelength converter

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Abstract. Gain-clamped wavelength converter is a key device for hybrid WDM/TDM passive optical network (HPON) based on all-optical wavelength conversion (AOWC). In this paper, the overshoot characteristic in converted signals of GCWC is numerically analyzed based on single-mode rate equation and large-signal analysis. The simulation shows that overshoot of converted signals could be decreased by increasing the bias current, length of active region, or reducing input signal power. And it also reveals that reflectivity of fiber Bragg grating has little effect on it. According to the above, structure parameters and operating parameters of GCWC are optimized. The experimental investigation shows great agreement with theoretical calculation.

1. Introduction

With the development of triple play service, passive optical network (PON), as a key technology to optical access network, tends to be long-reach access and large area covering to reduce the end-to-end cost of bandwidth and simplify the network. Current TDM-PON (Ethernet-PON and Gigabit-PON) architectures are economically feasible, but inevitably sacrifice per-subscriber bandwidth by sharing a single wavelength channel with multiple subscribers. WDM-PON offers great security and protocol transparency, and accommodates more subscribers without sacrificing bandwidth by adding wavelength channels, but the components in it are relatively expensive. A novel hybrid WDM/TDM passive optical network (HPON) based on all-optical wavelength conversion (AOWC) with high capacity and long reach and a single-fiber transmission is proposed. In AOWC-HPON architecture, wavelength conversion is a key technology to combine TDM and WDM. Several wavelength
conversion mechanisms have therefore been presented in the past; e.g. cross-gain modulation, cross-phase modulation and Four-Wave Mixing in semiconductor optical amplifiers (SOAs). Conventional wavelength conversion techniques cannot meet the requirements in AOWC-HPON architecture due to the drawbacks of needing external CW-probe, low conversion efficiency, not implementing up-wavelength conversion efficiently, or having small dynamic range.

In this paper, a novel gain-clamped wavelength converter (GCWC) is proposed to make the AOWC-HPON architecture feasible. The overshoot characteristic in converted signals of GCWC is theoretical and experimental investigated.

2. Time domain model of GCWC
A GCWC consists of a titled-waveguide SOA chip (residual reflection <10⁻³) and a pair of FBGs shown in figure 1. GCWC is modulated directly by input signals, implementing inverted wavelength conversion. The waveform of converted signals exhibits relaxation oscillations (overshoot) because of a time dependent energy exchange between laser field and carrier population in GCWC.

![Figure 1. Schematic of gain-clamped wavelength converter.](image)

We use the following rate equation model to study the overshoot characteristic of GCWC, taking into account the effects of nonlinear gain suppression:

\[
\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_e} - v_g G_1 (1 - \varepsilon_1 S_1 - \varepsilon_12 S_{in}) S_1 - v_g G_2 (1 - \varepsilon_21 S_1 - \varepsilon_22 S_{in}) S_{in}
\]

(1)

\[
\frac{\partial S_1}{\partial t} = \Gamma v_g G_1 (1 - \varepsilon_11 S_1 - \varepsilon_12 S_{in}) S_1 - \frac{S_1}{\tau_p} + \frac{\Gamma \beta_{gr} N}{\tau_e}
\]

(2)

The effective photon lifetime of converted wavelength \(\tau_p\), which is important to gain-clamped wavelength conversion, is expressed as

\[
\tau_p = n_L L_{in} + 2n_L L_{ex} \left( \frac{L_{in} - 2\eta_L L_{ex} (1 + r_g^2) \ln(\eta g^r)/(1 - \eta^2 r_g^2)}{\alpha L_{in} - 2\ln(\eta g^r)} \right)
\]

(3)

GCWC is typically biased close to threshold and modulated considerably above threshold to obtain optical pulses representing digital bits in HPON system. In this case of large-signals modulation, the rate equations should be solved numerically.
3. Numerical Simulation and Analysis

According to the previous model, we simulate the overshoot of converted signals using large-signal analysis. The parameters used in our simulation are shown in table 1.

| Parameters                                      | symbol | value     | unit  |
|-------------------------------------------------|--------|-----------|-------|
| Signals wavelength                              | $\lambda_S$ | 1530      | nm    |
| Extinction ratio of input signals               | ER     | 10        | dB    |
| Active area width                               | w      | 2         | $\mu$m |
| Active area thickness                           | d      | 0.2       | $\mu$m |
| Effective group index of refraction in cavity   | $n_1$  | 3.4       |       |
| peak wavelength of gain spectrum                | $\lambda_p$ | 1550      | nm    |
| Lasing wavelength                               | $\lambda_c$ | 1557      | nm    |
| Transparency carrier density                    | $N_t$  | 0.8×10$^{18}$ | cm$^{-3}$ |
| Differential gain coefficient                   | $d g/dN$ | 4.0×10$^{-16}$ | cm$^{2}$ |
| Power confinement factor                        | $\Gamma$ | 0.49       |       |
| Internal wavelength losses                      | $\alpha$ | 2×10$^{-3}$ | $\mu$m$^{-1}$ |
| Linear recombination coefficient                | A      | 5.0×10$^{8}$ | s$^{-1}$ |
| Bimolecular recombination coefficient           | B      | 870       | $\mu$m$^{3}$s$^{-1}$ |
| Auger recombination coefficient                 | C      | 9.5×10$^{-5}$ | $\mu$m$^{6}$s$^{-1}$ |
| Spontaneous emission factor                     | $\beta_{sp}$ | 0.001     |       |
| Nonlinear self gain suppression coefficient      | $\varepsilon_{11},\varepsilon_{22}$ | 6.8×10$^{-17}$ | cm$^{3}$ |
| Nonlinear cross gain suppression coefficient     | $\varepsilon_{12},\varepsilon_{21}$ | 13.6×10$^{-17}$ | cm$^{3}$ |
| Coupling efficiency                             | $\eta$ | 0.49      |       |

3.1. The influence of operating parameters.

In this section, we will investigate the influence of some operating parameters on overshoot of converted signals. The peak value of normalized overshoot as a function of bias current and average input signal power is given in figure 2 and figure 3. It can be seen from figure 2 that the peak value of normalized overshoot of converted signals is decreased from 0.25 to 0.1 by increasing the bias current from 130 mA to 170 mA. This is directly related to the carrier variation in active region.

![Figure 2. Overshoot of converted signals vs bias current (L_in=0.8 mm, r_g=0.5, P_in=-3 dBm)](image-url)
Figure 3 shows that the peak value of normalized overshoot of converted signals increases from 0 to 0.9 when the input signal power changes from -10 dBm to 4 dBm. We can clearly see that lower input optical power causes the better performance of overshoot in converted signals. It should be noted that input signal power beyond a certain value will shut down the gain-clamping lasing in GCWC.

3.2. The influence of structure parameters.

Figure 4. Overshoot of converted signals vs length of active region ($r_g=0.5$, $I_b=150$ mA, $P_{in}=-3$ dBm).

Figure 5. Overshoot of converted signals vs reflectivity of FBGs ($L_m=0.8$ mm, $I_b=150$ mA, $P_{in}=-3$ dBm).
The overshoot characteristic of GCWC is strongly dependent on the length of active region. This dependence is illustrated in figure 4. From figure 4 we can conclude that the peak value of normalized overshoot of converted signals monotonely increases with the length of active region. Because the injected current density will decrease with increasing the length of active region. Furthermore, it should be paid attention in practical applications that decreasing the length of active region could lead to a serious degradation of extinction ratio of converted signal.

Figure 5 shows the influence of reflectivity of FBGs on overshoot of converted signals. As seen from the figure, overshoot is affected to some extent by reflectivity of FBGs, but not very seriously.

4. Experimental results

According to the simulation results, the optimized structure parameters are as the following: the length of active region operating at 1.550 μm is 800 μm, the reflectivity of FBGs is 0.5 with bandwidth of 0.3 nm @-3 dB. Based on the above-mentioned structure, the optimized operating parameters are obtained as follows: the input signal power is -3 dBm, bias current is 150 mA. The experimental setup is presented in figure 6, which converts the signal wavelength at 1530 nm to the clamped-wavelength at 1557 nm. The converted signals is filtered out by a band-pass filter.

Figure 7 and figure 8 show the converted waveforms for different input optical power (-3 dBm and 0 dBm). The most remarkable notice is the wavelength converted signals undergoes significant overshoot on the rising edge while little undershoot on the falling edge. The results show that overshoot could be decreased by reducing input signals power. The experimental results agree well
with the theoretical calculation.

![Figure 9](image_url)

**Figure 9.** Input dynamic range of GCWC for HPON application

Figure 9 shows the BER performance for the converted wavelength under different bias current. The results confirmed that it is possible to achieve BER performance of $10^{-10}$ for AOWC-HPON application with an input dynamic rage up to 11 dB. This means GCWC of the above-optimized parameters can implement wavelength conversion for burst signals with power different value of 11 dB. Although the overshoot of converted signals is monitored through a communications signal analyzer (CSA) when GCWC working at optimal operating point ($P_{in}=-3$ dBm, $I_b=150$ mA), according to figure 7, the BER performance of converted signals can still achieve $10^{-12}$.

5. Conclusion
In this paper, the overshoot characteristic in converted signals of GCWC is numerically analyzed based on single-mode rate equation and large-signal analysis. The simulation shows that overshoot of converted signals could be decreased by increasing the bias current, length of active region, or reducing input signal power. And it also reveals that reflectivity of fiber Bragg grating has little effect on it. According to the above, structure parameters and operating parameters of GCWC are optimized. The experimental investigation shows great agreement with theoretical calculation.

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References
[1] Dong J J, Zhang X L, Huang D X 2005 *Acta Phys. Sin.* **59** 1021
[2] Sebastian W, Weng W C, Lukas C, Connie J C H 2006 *Quant. Electron.* **42** 552
[3] Jin Y S, Geert M, Roel B 1997 *Quant. Electron.* **3** 1162
[4] Farhan R, Paul G 2007 *Quant. Electron.* **43** 1109
[5] D M Kane, Joshua P T 2009 *Quant. Electron.* **27** 2949
[6] Victor T Company, Kamau P, Idelfonso T M 2008 *Photon. Technol. Lett.* **20** 1299
[7] Zhao T G, Ren J H, Li W, Zhao R H 2003 *Acta Optica Sinica* **23** 1071
[8] Govind P A 2001 *Fiber-Optic Communications Systems* (American: John Wiley & Sons, Inc.) P110
[9] Dong J J, Zhang X L 2007 *Chin. Phys. Lett.* **14** 990
[10] Dong J J, Zhang X L, Huang D X 2007 *Chin. Phys. Lett.* **24** 3450
[11] Larry A C and Scott W C 2006 *Diode Lavaers and Photonic Integrated Circuits* (American: John Wiley & Sons, Inc.) P132