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Ultrahigh-Frequency Microwave Phase Shifts Mediated by Ultrafast Dynamics in Quantum-Dot Semiconductor Optical Amplifiers

Yaohui Chen and Jesper Mørk

Abstract—We present a novel scheme to achieve tunable microwave phase shifts at frequencies exceeding 100 GHz based on wavelength conversion induced by high-speed cross-gain modulation in quantum-dot semiconductor optical amplifiers.

Index Terms—Cross-gain modulation (XGM), quantum dot (QD), semiconductor optical amplifiers (SOAs), wavelength conversion.

I. INTRODUCTION

Controllable slow and fast light has been experimentally demonstrated in different active semiconductor waveguide devices at room temperature by exploiting the effect of coherent population oscillations (CPOs) [1]–[3]. From an application point of view, it is of significant interest to realize an optically fed microwave phase shifter based on semiconductor devices, such as semiconductor optical amplifier (SOA), with a variable phase shift range of \(2\pi\) at gigahertz modulation frequencies. SOA-based phase shifters investigated so far rely on dynamical gain gratings mediated by temporal modulation of the total carrier density in a single wavelength configuration [1]–[5]. The corresponding bandwidth is thus limited by the inverse of the carrier lifetime, i.e., typically on the order of a few to several gigahertz under forward bias. Different approaches towards alleviating the bandwidth limitation have been reported [4], [5]. An alternative configuration is to use cross-gain modulation (XGM)-based wavelength conversion in a distributed-feedback (DFB) laser [6]. Recent calculations and experiments indicate that quantum dot (QD)-based devices are good candidates for high-speed optical signal processing due to the unique ultrafast intersubband carrier dynamics between discrete QD bound states [7]–[11]. In addition, this configuration allows an alternative way of characterizing ultrafast QD intraband dynamics.

II. PRINCIPLE OF OPERATION AND MODELING

Fig. 1(a) shows the considered wavelength up-conversion configuration based on QD SOAs. It is similar to the small-signal XGM configuration in [12] with a sine-modulated data signal, at optical frequency \(\omega_{\text{DATA}}\), as input (given by \(P_{\text{DATA}}^\text{IN} [1 + m_0 \cos(2\pi ft)]\), where \(P_{\text{DATA}}^\text{IN}\), \(m_0\), and \(f\) are input power, modulation index, and modulation frequency). The data signal will modulate the gain of the SOA and thus in turn XGM in the amplifier will transfer the modulation to the copropagating continuous-wave (CW) signal at optical frequency \(\omega_{\text{CW}}\) as an XGM converted signal with an inverse pattern. For simplicity, by ideal flat-top selective optical bandpass filtering, the output intensity envelope centered around \(\omega_{\text{DATA}}\) and \(\omega_{\text{CW}}\) can be detected in the form of \(P_{\text{DATA}}^\text{OUT} [1 + m_{\text{OUT}} \cos(2\pi ft + \phi_{\text{OUT}})]\). Here, \(P_{\text{DATA}}^\text{OUT}\), \(m_{\text{OUT}}\), and \(\phi_{\text{OUT}}\) (\(X = \text{CW, DATA}\)) are the mean output optical intensity, modulation index, and radio-frequency (RF) phase shift at the given optical frequency. The corresponding RF optical gain is in the form of \(P_{\text{DATA}}^\text{OUT} m_{\text{OUT}} / (P_{\text{DATA}}^\text{IN} m_0)\). Note that there are two main changes compared to previous results. First, the optical frequencies of the data signal (\(\omega_{\text{DATA}} = \omega_E\)) and CW signal (\(\omega_{\text{CW}} = \omega_E\)) are chosen corresponding to dynamic gain gratings induced by high-speed XGM in QD SOAs. In contrast to the usual configuration involving a weak probe and strong pump, this concept utilizes the two-wave competition phenomenon [12], namely the strong interaction between two waves with comparable magnitude, caused by XGM via fast intersubband effects in QDs under a high current injection. The main new results compared to previous works are to numerically demonstrate the potential of QD SOAs for this new application as a simple and compact \(~180^\circ\) broadband microwave phase shifter working at frequencies beyond 100 GHz. In addition, this configuration allows an alternative way of characterizing ultrafast QD intraband dynamics.
the two lowest discrete QD bound states, i.e., excited (E) and
ground (G) state, which are connected by fast (subpicosecond)
intersubband electron relaxation. The frequency detuning
(\(\omega_{\text{DATA}} - \omega_{\text{CW}} = \omega_{E} - \omega_{G}\)) is assumed much larger than the
homogenous linewidth of the QDs, and thus FWM interaction
between data and CW signals are neglected. Second, the input
CW power \(P_{\text{CW}}^{\text{IN}}\) is variable and acts as a strong pump, while
the average input data power \(P_{\text{DATA}}^{\text{IN}}\) is constant and relatively
weak. Therefore, the dynamic gain grating is no longer solely
determined by the data signal as in the small-signal regime.
Instead, both the data and XGM-converted signal are considered
to compete for the available carriers and interact with dynamic
gain gratings (at frequencies \(\omega_{\text{DATA}}\) and \(\omega_{\text{CW}}\)) via XGM
in terms of the two-wave competition.

The QD SOA's model is based on the rate equation ap-
proach originally developed for carrier dynamics in 1100-nm
InAs–GaAs QDs [13], which describes the carrier scattering
between QD subbands and Reservoir (R) including Wetting
layer and barrier. Inhomogeneous gain broadening of self-assembled
QDs and homogenous broadening of stimulated emission/ab-
sorption are included. A local carrier density description of QD
bounded hole states with 100-fs valence intraband scattering
time has been used. The maximum modal gain values are
24 cm\(^{-1}\) at the center of \(G\) state transition and 38 cm\(^{-1}\) at
the \(E\) state peak. The device is 2 mm long and has an internal
loss of 2 cm\(^{-1}\). For the electron dynamics at strong current
injection (10 kA/cm\(^2\)), the longest characteristic time scale
(\(~0.7\) ns) is the \(R\) state carrier lifetime, the intermediate time
(2.5 ps) is the electron capture from \(R\) to \(E\) (or \(G\)) states, and
the shortest time (0.2 ps) is the intradot electron relaxation from
\(E\) to \(G\) states. These time scales were extracted from two-color
pump–probe measurements [14] and many-body calculations
[15]. Here, optical intensity propagation equations have been
used and dispersive effects are not included. In this work, we
emphasize the phase shifting profile of the XGM converted
signal (\(\omega_{\text{CW}}\)) after the QD SOAs for a strong current injection
(10 kA/cm\(^2\)).

Fig. 2(left) shows the calculated static modal gain of QD
SOAs for different values of the input CW power. As the
stimulated emission at frequency \(\omega_{\text{CW}}\) (input CW power)
increases, spectral holes are seen to develop in the gain spec-
trum, centered at the \(E\) and \(G\) states. Notice that the spectral
hole burning corresponding to the \(E\) state transition originates
from the large contrast between the fastest intradot electron
relaxation and the intermediate electron capture from \(R\) to \(E\)
states, which is synonymous to the existence of an injection
bottleneck due to long capture time or short escape time [16].
As the rate of removal of carriers in the QD \(G\) state due to
stimulated emission approaches the injection rate between
reservoir and QDs, it is possible to deplete the \(E\) state carrier
population and thus even switch from gain to absorption.
Now, in the presence of a modulated data signal, let us consider
the modal gain at frequency \(\omega_{\text{CW}}\) in the form of a Fourier series:
\(\bar{g} + \sum_{n=1}^{\infty} [\Delta g_{n} \exp(i2\pi ft + i\Delta \phi_{n}) + c.c.] / 2\). Here, \(\bar{g}\)
is the static gain, and [\(\Delta g_{n}\) and \(\Delta \phi_{n}\) are the modulated
gain and phase for the \(n\)th order harmonics. In this letter, the
modulation index of input data signal \(\omega_{\text{DATA}}\) is fixed at
20%. As the higher order harmonics give small contributions
(distortion) to the overall XGM, we only keep the first-order
harmonics. The XGM response, \(\Delta g_{n}/(P_{\text{DATA}}^{\text{IN}}/P_{\text{DATA}}^{\text{IN0}})\), and the
relative phase, \(\Delta \phi_{n}\), are shown in Fig. 2(right). Flat XGM
responses approximately up to 100 GHz are observed, which
As the CW power is modest, the XGM responses in the low
modulation frequency range have a phase shift of around \(\pi\)
relative to the modulation of the input data signal, which is
similar to wavelength conversion with an inverse pattern in the
small signal regime [10]. As the CW power is strong and
depletes the gain of \(E\) state into absorption, a \(\pi\)-shift of the
XGM response is consistent with switching to “noninverting”
cross-absorption modulation (XAM) [17]. Thus, by increasing
the input CW power, the XGM converted signal experiences
the corresponding \(\pi\)-shift and also benefits from the efficient
conversion at high modulation frequencies.

III. PHASE PROFILE IN WAVELENGTH CONVERSION

Fig. 3 shows the calculated characteristics of the RF output
signal at a modulation frequency of 40 GHz in our wavelength
conversion configuration under strong current injection. We fix
the input data signal at 1 mW to retain a reasonable signal-to-
noise level. Fig. 3(top) shows a ∼180° tunable phase shift ϕ_{\text{OUT}}^{\text{CW}} for the XGM converted output by controlling the input probe power. The sharp increase of the phase shift corresponds to the notch-type drop of the XGM efficiency (related to the RF optical gain) seen in Fig. 3(bottom) at frequency ω_{\text{CW}}. By evaluating the mean output optical power in Fig. 3(bottom), the wavelength conversion in QD SOAs can be divided into two regimes: a small-signal regime (P_{\text{OUT}}^{\text{CW}} \ll P_{\text{DATA}}^{\text{OUT}}) and a two-wave-competing regime (where P_{\text{OUT}}^{\text{CW}} is comparable to or much larger than P_{\text{DATA}}^{\text{OUT}}). In the small-signal regime, only the data signal dominates the dynamic gain grating and a linear increase of XGM efficiency can be observed. The intensity envelopes of the output data signal and the XGM converted signal are nearly out of phase (∼180°) for ϕ_{\text{OUT}}^{\text{CW}} = ϕ_{\text{DATA}}^{\text{OUT}}. In the two-wave-competing regime, the dynamic gain gratings depend on the mean power of the spatially varying CW signal. As the stimulated emission at the G state transition reaches the maximum value imposed by the injection bottleneck, the amplifiers can be regarded as being spatially divided into a usual XGM section and an XAM section. Thus, the intensity envelope of the XGM signal experiences a π-shift in between these two sections, which results in a notch-type drop in the XGM efficiency and a ∼180° phase shift.

Fig. 4 shows the XGM converted output signal as a function of modulation frequency for different input CW power levels. Due to the fast intersubband carrier dynamics between E and G states, the dynamic gain grating (at frequencies ω_{\text{DATA}} and ω_{\text{CW}}) can balance and follow each other at high-speed modulation. It is seen that a shift of π can be achieved by changing the input power from 5 to 30 mW for modulation frequencies even beyond 100 GHz. For different modulation frequencies, different input power levels are required to achieve a given phase shift, such as π/4, π/2, 3π/4, etc. We also notice that the corresponding RF optical gain changes significantly, which is an undesirable feature. This feature is related to the properties of the dynamic gain grating as a function of modulation frequency shown in Fig. 2(right). Especially in the two-wave-competition regime, the magnitude and phase of the XGM response vary for different modulation frequencies even for identical mean power. Therefore, the cancellation and reconstruction of the XGM converted signal (notch-type drop appearance of RF optical gain in Fig. 3) are sensitive to both modulation frequency and input CW power. In practice, there is a trade-off between the maximum modulation frequency and the minimum signal power to retain a reasonable signal-to-noise ratio.

IV. CONCLUSION

We numerically demonstrated a scheme to realize a ∼180° broadband microwave phase shifter based on high-speed XGM in QD SOAs under strong current injection. The modulation bandwidth is predicted to be beyond 100 GHz, limited by the fast intersubband carrier dynamics in QDs.

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