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Controlling the Speed of Light in Semiconductor Waveguides: Physics and Applications

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Abstract: We review the physics of slow and fast light effects in semiconductor optical waveguides. Recent experimental and theoretical results on enhancing the phase shift using optical filtering are presented and applications in microwave photonics are discussed.

OCIS codes: (190.5970) Semiconductor nonlinear optics including MQW; (250.5980) Semiconductor optical amplifiers

The experimental demonstrations of slowing light in atomic gasses [1] have led to a significant interest in exploring the physics and applications of this phenomenon. Practical applications, e.g. within microwave photonics [2] and optical communications, favour a technology which allows cheap and compact devices with potential for integration and recent results on semiconductor waveguides indicate a strong potential [3-9].

The effect of electromagnetically induced transparency (EIT), demonstrated so successfully in atomic gasses [1], is hard to realize in semiconductor media due to their strong degree of inhomogeneous broadening and very short dephasing times. Both effects make it difficult to realize the quantum mechanical coherence between levels which is required for EIT [11]. Instead, one has exploited the effect of coherent population oscillations [10], for a review see [11]. This effect relies on the beating between external laser beams that excite the semiconductor, which leads to a modulation of the carrier distribution in the semiconductor and subsequent changes of the refractive index and its dispersion. The effect can in general be analyzed in the frequency domain using four-wave mixing theory.

Due to the fundamental properties of the CPO effect, where the index change is closely linked to the carrier lifetime describing the recovery time of a gain change induced by saturation, it does not appear feasible to exploit this effect for all-optical buffering [4]. Rather, applications in microwave photonics seem promising. For specific applications in phased array antennas ad microwave filters, however, it is necessary to realize a 360 degrees phase shift, which has not yet been experimentally demonstrated. The cascading of waveguides with alternating gain and absorption may be one way to scale the phase shift obtained in single waveguide sections [7], but due to the absorption introduced in this configuration the build up of spontaneous emission noise needs to be investigated further. Recently, another technique for increasing the phase shift was suggested and experimentally demonstrated, see Fig. 1. By using optical filtering prior to photodetection it was shown that the phase shift can be significantly enhanced [12]. The origin of this effect is the dynamics of the refractive index, which leads to a phase shift of the sidebands. Normally this effect is cancelled out when using a double-sideband signal [4]. For a detailed analysis see [13].

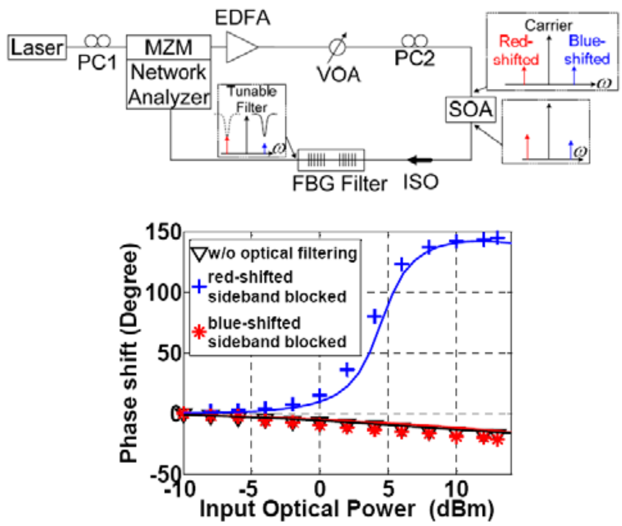

Fig. 1. Experimental set-up (upper) and results (lower) for the case of performing optical filtering before detection [12]. A fiber-grating (FBG) notch filter allows one of the sidebands to be blocked before detection without influencing the carrier or the other sideband. The modulation frequency is 19 GHz. Markers are experimental data and solid lines are numerical simulations. Three cases are shown: no filtering (black); blocking the blue-sideband and letting the red pass (red); blocking the red sideband and letting the blue pass (blue). The simulations were performed using a four-wave mixing model for the interaction of the different sideband, taking into account only the dynamics of the total carrier density.

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As an example of an application of this scheme for controlling the phase, Fig. 2 shows the implementation of a tunable microwave filter [14]. The filter is composed of a Mach-Zehnder intensity modulator (MZM), a commercial SOA, and an FBG filter. The RF signal with microwave frequency Ω is modulated onto a CW laser beam with the frequency f_0 through the MZM, generating two weak sidebands, blue-shifted sideband $f_0+\Omega$ and red-shifted sideband $f_0-\Omega$. By operating the MZM at different slopes, V_1 =4.5 V and V_2=8.1 V, both ~0º and ~180º optical phase difference between the strong carrier f_0 and the two sidebands can be imposed. By inserting an FBG notch filter after the SOA to suppress the red-shifted sideband, ~120º phase delay as well as ~170º phase advance at a microwave frequency of 19 GHz can be achieved for ~0º and ~180º initial optical phase differences between the carrier and sidebands, respectively. This means that by combining this phase delay and phase advance, a ~360º phase shifter can be realized. Fig. 2 illustrates the tunable microwave filter response that can be obtained by controlling the phaseshift. As shown in [14] the filter response can be tuned by nearly one free spectral range without influencing the shape.

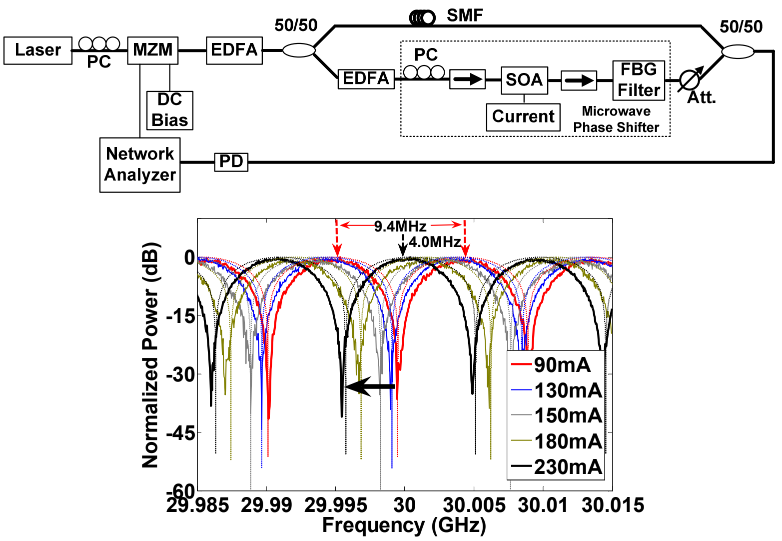

Fig. 2. Experimental set-up of a two-arm microwave photonics notch filter (upper) and measured filter response (lower) [14]. Notice that the path difference between the two arms is chosen long enough that the optical fields from the two arms combine *incoherently*. The RF response of the microwave photonic notch filter obtained by changing the injection current of the SOA is shown for the modulator biased at a voltage of 4.5 V. A similar but opposite shift of the filter response is obtained when the modulator voltage is set at 8.1 V. The dotted lines are simulation results based on a simple four-wave mixing model.

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