Frozen-Light Modes in
3-way Coupled Silicon Ridge Waveguides

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***Abstract*— Frozen-light modes supported by the stationary inflection point (SIP) within the pass band of 3-way coupled periodic silicon ridge waveguides is demonstrated. Precise tuning of the coupling between forward and backward propagating modes lead to mode degeneracy with vanishing group velocity. The unit cell is tuned to obtain the SIP on the third branch in the dispersion diagram. Subsequently, we demonstrate a finite structure with 23 unit cells to support the frozen mode at the SIP frequency. For this example, the group velocity at the SIP is 385 times slower than speed of light in vacuum. Transmission resonances of the finite structure, as well as the field distribution within the device at the SIP frequency are studied and presented.**

I. INTRODUCTION

Slowing down electromagnetic wave propagation through dispersion engineering has been beneficial for many applications in optical and microwave regimes. Among the key benefits are controlled optical signal delay, improved wave amplification and mixing, and high power microwave generation through plasma interactions. Slowing down light beams by orders of magnitude, or even with vanishing group-velocity have been realized mainly through two techniques. First, the boundaries between strongly-dispersive media can lead to wave slow-down [1]. Alternatively, in periodic media exhibiting stop bands lead to zero group velocity at the band edges. For example, anisotropic photonic crystals can be designed to control the dispersion of the composite, leading to rich coupled mode behavior [1]-[3]. Guided wave structures, such as microstrip waveguides, can also be designed to mimic the modes of anisotropic photonic crystals and provide many of the properties of multi-dimensional structures, but with reduced footprint and fabrication complexity [4, 5].

As noted above, slow wave resonances with vanishing derivatives of group velocity are only achievable at the band edges of non-magnetic photonic crystals, such as those in degenerate band edge (DBE) structures. However, since band edge frequencies do not allow a direct excitation, the actual wave slow-down in the vicinity of the band edge depend on the number of unit cells used to realize the structure. The Fabry-Perot resonance closest to the band edge dictates the ultimate group wave velocity [1]. A key difference of magnetic photonic crystals is that they allow for mode degeneracy where a stationary inflection point (SIP) behavior within the propagation band can be achieved [3]. A similar behavior is not possible in coupled periodic guiding structures. However, 3-way coupled structures allow for 3 dispersion branches and careful tuning of coupling can achieve the SIP behavior, even in the absence of magnetic materials. Coupling between forward and backward modes on the 3 adjacent coupled waveguides lead to symmetric SIPs in their dispersion diagram, as first realized in [6]. The dispersion relation for SIP can be approximated as $\Delta w \; \alpha \; \Delta k^3$, where w and k are the frequency and wavenumber, respectively. Here, we present a 3-way coupled silicon ridge photonic waveguides, and, demonstrate the frozen mode in the dispersion associated with the SIP, leading to significant time delay enhancement.

II. FROZEN MODE IN COUPLED RIDGE WAVEGUIDES

In this work, 3-way coupled periodic silicon ridge waveguides with one-dimensional periodicity are designed to tune the group velocity dispersion and achieve a SIP within the first allowed band of the structure. To do so, we started with a periodic ridge waveguide where the perforations of the top and

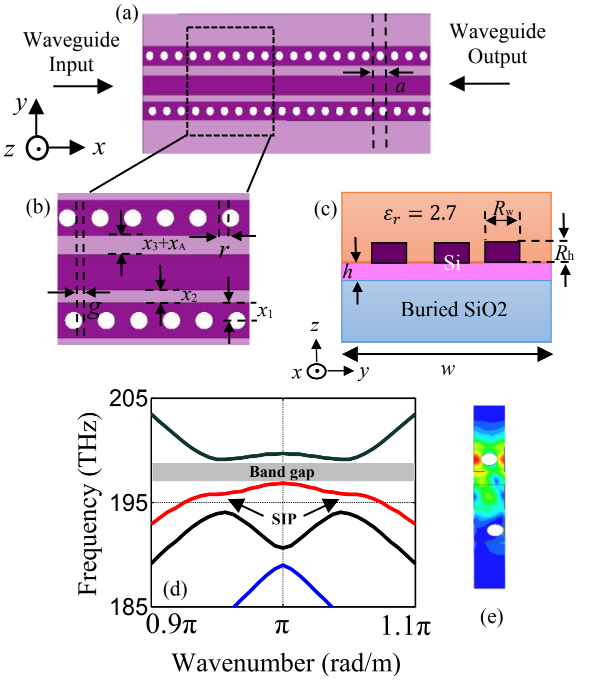

Fig. 1. Schematic of the 3-way coupled periodic silicon ridge waveguides: (a) Top view of the device, (b) zoomed top view, (c) cross-sectional view, (d) dispersion relation, where, $v_g = \partial w/\partial k = 0$ at the SIP as shown in the third mode in red at 195.7 THz, (e) electric field distribution at the SIP frequency.

bottom waveguides were shifted and fine-tuned to create three forward and backward waves that couple to generate the frozen light.

This design was targeted for the S-C-L optical bands with a periodicity of a = 370 nm, (around λ/4 of guided wavelength). The device consists of three silicon ridge waveguides next to each other with refractive index of 3.45, situated on a 1 µm thick buried oxide layer with refractive index of 1.45. A 1µm thick material with permittivity of 2.7 covers the whole structure. The ridge waveguide has an overall width of w = 3 um, thickness h = 20 nm, ridge width R_w = 400 nm, and ridge thickness R_h = 150 nm. The holes of the device are shifted along the propagation direction by g = 70 nm. The radius of the holes is r = 100 nm, and, x_1 = 200 nm, x_2 = 145 nm, and, $x_3 + x_A$ = 220 nm, as shown in Fig. 1(a), (b), (c).

The close-up of the first Brillouin Zone (0.9 π to 1.1 π) is shown in Fig. 1 (d) and clearly shows the 3 branches of the dispersion relation of coupled ridge waveguides. This diagram depicts only the transverse electric (TE) modes of the waveguide, where the dominant electric field component is in the y-direction. As noted above, the SIP can be tuned by shifting the holes on the bottom guide in the propagation direction (by g = 70 nm) and concurrently by shifting the top ridge waveguide away from the middle by x_A = 75 nm. Shifting the periodic holes in the bottom guide in the propagation direction tunes the contra-directional coupling and adjusting the distance between the ridge waveguides controls the degeneracy of the 6 modes existing in the 3-way coupled structure. At the SIP, two forward propagating modes couple with the backward propagating mode, leading to the unique SIP behavior. At the SIP, the group velocity dispersion $v_g = \partial w/\partial k = 0$, as shown in the red curve in Fig. 1 (d). Also, Fig. 1 (e) shows the field distribution of the degenerate mode (at the SIP frequency) inside the unit cell. As seen, the field is confined mostly within one side of the device with red color which representing the maximum field amplitude.

III. FINITE-LENGTH COUPLED WAVEGUIDE SUPPORTING THE FROZEN MODE

In order to practically realize a 3-way coupled photonic guide supporting a frozen mode, a finite length structure must be studied. Here, we considered a 3-way coupled periodic silicon ridge waveguide with N = 23 periods, and characterized its behavior using full wave electromagnetic simulation (Ansys HFSS v.19). The number of unit cells was chosen large to observe the significant field amplitude build up and to measure the group delay and transmission at the SIP. As seen in Fig. 2 (a), only a single port at the input side and a single port at the output side was considered, and the remaining ports were terminated by matched ports.

Uncoupled sections were used to bring the 3 ridge guides close together and allow for optical fiber coupling. Also shown in Fig.2 (a) is the electric field distribution within the coupled photonic guide at the SIP frequency of 195.7 THz. As seen, the coupling of the light from the excited bottom guide onto the top guide, as well as the field amplitude build up (a key result of wave slow down [1]) are clearly observed. The overall transmission and reflection properties of the 3-way coupled photonic guide is shown in Fig. 2 (b). We note that although the SIP frequency in Fig. 1 (d) appears close to the first band gap, it is clearly within the propagation band. As such, the Fabry-Perot resonance in Fig. 2 (b) achieves 80% transmission at the SIP frequency.

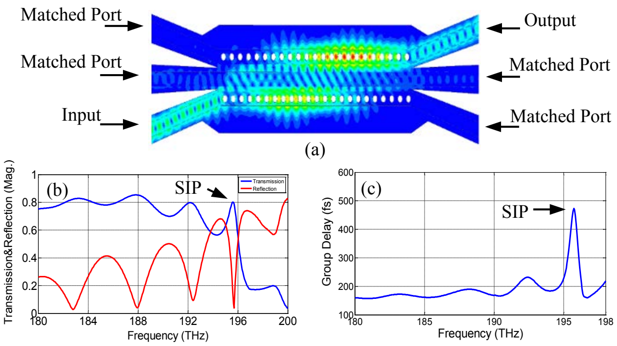

Fig. 2. Full wave simulation of the 23 unit cells of the 3-way coupled periodic silicon ridge waveguides: (a) Electric field distribution at SIP in magnitude (maximum value is in red, minimum value is in blue), (b) transmission and reflection of the finite structure, (c) Absolute value of the group delay where it shows the maximum value at the SIP (195.7 THz).

The computed group delay in the vicinity of the SIP frequency is shown in Fig. 2 (c). Compared to the physical length of the 23-unit cell coupled structure, the group velocity ($v_g = L/t_d$) of the frozen mode is about 385 times slower than speed of light in free space. Here, the group delay of this structure was calculated as $t_d = 475$ fs and is occurs at the SIP frequency. Even with such a slow group velocity, the overall losses of the 23-unit cell structure is quite large (at 80% overall transmission).

IV. CONCLUSION

The frozen mode supported by the SIP in the dispersion of 3-way coupled photonic waveguides is demonstrated. Periodic holes were introduced in the ridge guide design to enable degenerate mode coupling and the fine-tuning of the ridge topology resulted in the SIP behavior. We also demonstrated that a finite-size structure made of 23 unit cells also supports the frozen mode, with much longer group delay (385 times slower than speed of light in the vacuum) and much increased optical fields within the guides.

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