Dynamically tunable mirrors for THz free electron laser applications

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We have constructed and tested 1D-photonic crystal (PhC) mirrors with tunable reflectivity to be used as efficient, broadband outcouplers for THz free electron lasers (FELs). The test mirrors cover a spectral range between 0.5 and 1.5 THz. They are assembled by stacking up quarter-wave dielectric layers separated by vacuum. The adopted PhC mirror design enables dynamical (while lasing) adjustment of individual layer spacing. Single as well as multiple defects in the periodicity are introduced to invoke a continuous, well-defined tuning of reflectivity and outcoupling ratio. The scheme allows one to vary also the PhC period while the equidistant spacing between the layers is maintained. This feature is used to shift the photonic band gap (center) for achieving an effective extension in the reflectance spectrum. Because of the exceptional flexibility provided by the scheme in tailoring the characteristics of the PhC defects, additional features such as tunable (narrow) bandpass filtering as well as (fast) THz intensity modulation can be combined with the reflectivity/coupler characteristics of the proposed PhC mirrors for FELs.

I. INTRODUCTION

Outcoupling efficiency is a crucial parameter in defining the peak and average free electron laser (FEL) power available for user experiments as well as reducing the heat load deposited on the resonator structure in high power FEL systems. While the commonly used metallic mirror “hole” outcouplers offer a relatively simple means of broadband outcoupling in the THz region, their efficiency remains low at ~50% [1]. The remaining part of the radiation power dissipates by mode conversion as Ohmic loss into the mirror/waveguide assembly. Previously, within the frame of a THz FEL design study [2,3], we have proposed the use of intracavity (silicon) beam splitters as outcouplers [4] to alleviate the problem. However, in view of superior tuning characteristics and ease of operation, a study has been initiated to examine also the possibility of adopting low-loss dielectric multilayer [Bragg or 1D photonic crystal (PhC)] structures as outcoupler and high reflectivity mirrors for the construction of high-Q THz cavities [3]. Because of the nearly 100% outcoupling efficiency provided by these PhC reflectors, the outcoupled THz FEL pulse energy (power) can be doubled as compared to the widely used hole-type outcouplers. In addition, the negligible mode distortion (uniform coupling ratio across the beam cross section) achieved at the coupling makes them also an ideal coupler type for injecting the generated FEL pulses into an external THz pulse stacker cavity [3,5]. Since THz FELs are high power radiation sources, it is imperative to employ low-loss materials within the cavity; chemical vapor-deposited (CVD) diamond (D), high resistivity (~10 kΩ cm) silicon (Si), and z-cut crystalline quartz (Q) are considered due to their low (power) absorption [α < 0.03 cm−1 [D and Si (10 kΩ)], α ~ 0.02–0.20 cm−1 (Q)] and a high index of refraction (nD = 3.41, nD = 2.37, nQ = 2.11) over the THz range of interest [6–8].

One-dimensional PhC mirrors have been constructed and tested for experiments in the THz spectroscopy previously [9–11]. The schemes presented in the current study introduce several novel aspects [12,13]: a fine (0.1% tuning accuracy), continuous tuning of reflectivity is accomplished by adjusting the interlayer spacing (single or multiple layers). The reflection/transmission characteristics of a 1D-PhC mirror are otherwise fixed due to a few, discrete number of low-loss dielectric layers used in its assembly. Overcoming this limitation, the studied scheme opens up a practical way to establish the broadband 1D-PhC mirrors for applications in THz FELs that are known to be continuously tunable devices over a large spectral range. It allows online adjustment of a well-defined coupling ratio at a given frequency within the high reflectivity band (photonic band gap) in order to optimize the FEL performance. Owing to the flexibility offered by the scheme in tailoring the optical properties of the PhC defects, features such as tunable (narrow) bandpass filtering as well as (fast) THz intensity modulation can be combined with the above-mentioned reflectivity/coupler characteristics. The latter creates new means of manipulating the intracavity buildup process in THz FELs as well as postprocessing the temporal/spatial properties of the generated intense THz FEL pulses [3,13]. In addition, the ability of varying the basic unit cell size (while employing the same dielectric wafers) helps to extend the operational reflectivity band of the PhC mirror, by nearly doubling it.

II. METHOD

A schematic layout of a THz FEL that employs a 1D PhC mirror is illustrated in Fig. 1. Two parallel metal plates
placed within a (planar) undulator gap and extending over the entire cavity act as a low-loss waveguide (PPW) structure allowing the excitation of hybrid (Gauss-Hermite) transverse waveguide modes [14]. The waveguided resonator comprises a metallic high reflectivity mirror and a PhC mirror providing broadband feedback and outcoupling. Figures 2(a) and 2(b) display the computed reflectance spectra of 1D PhCs formed by stacking quarter-wave, low-loss Si and z-cut quartz layers separated by vacuum. The thickness of the individual (dielectric, vacuum) layers is set to be \(n_c/4n\), \(\lambda_c\), and \(n\) denoting the targeted central wavelength and the layer’s refractive index, respectively. For the particular case of quarter-wave stack (QWS), the fractional bandwidth of the fundamental photonic band gap is maximized. It is given by [15]

\[
\frac{\Delta \lambda_{\text{gap}}}{\lambda_c} = \frac{4}{\pi} \sin^{-1} \left( \frac{n_d - 1}{n_d + 1} \right),
\]

where \(n_d\) is the refractive index of the dielectric layer.

The FEL can be tuned to operate at any wavelength \(\lambda_r\) within the high reflectivity band. PPW THz FELs operate typically at the fundamental mode with \(\lambda_r\) given by

\[
\lambda_r = \frac{\lambda_u}{\gamma^2 \beta_z [1 + \beta_z \sqrt{1 - \left(\frac{\lambda_{PC}}{2 \gamma^2 \beta_z g}\right)^2}]},
\]

where \(\beta_z\) is the normalized axial velocity of the relativistic electron beam, \(\gamma_z = (1 - \beta_z^2)^{-1/2}\) the longitudinal Lorentz factor, and “g” the waveguide gap. The continuous tunability of \(\lambda_r\) is accomplished via the beam energy and the undulator field strength which both determine the electrons’ axial velocity in the beam. \(\lambda_{PC}\) roughly relates to the undulator period \(\lambda_u\) shown in Fig. 1 in a simplified relation by omitting the waveguide dispersion as

\[
\lambda_{PC} = \frac{\lambda_u (1 + a_u^2) (1 + n_d)}{8 \gamma^2 n_d}.
\]

Here, \(a_u = 0.093 \cdot B_u [\text{kG}] \cdot \lambda_u [\text{cm}]\) is the undulator parameter, \(B_u\) being the on-axis magnetic field strength of the undulator. For many THz FELs \(\lambda_u(\sim 10 \text{ cm})\) is typically 3 orders of magnitude larger than \(\lambda_{PC}\).

The reflectance spectra in Fig. 2 shows also the presence of (odd) harmonic photonic band gaps. Although we stress here the application to the fundamental photonic band gap, the studied tuning concept is valid for the higher harmonics as well. An important application that makes use of the third harmonic will be detailed further below.

As illustrated in Fig. 3, the online reflectivity/transmission tuning schemes, that are implemented in the tested PhC mirrors, can be categorized into three major groups regarding their functionality. The schemes shown in the first group (I.a–I.c) suit well for serving as fine-tunable
FEL outcoupler mirrors. Introducing the reconfigurable defects shown in this first group, rather modest tuning rates (\(\sim 0.1\%–1\%\) change in transmission due to a micron displacement of the movable layer) can be realized at around the desired coupling ratio. Since THz FELs are usually high gain devices, in order to be tuned to an optimum outcoupling ratio the PhC mirror’s tuning range should cover transmission values reaching from 0 up to several tens of percentages. Note that the multilayer structure shown in I.a (Fig. 3) can be viewed as a thin, asymmetric Fabry-Perot (FP) etalon consisting of a high and a lower reflectivity mirror with adjustable cavity length \(l_c\), i.e., a FP interferometer (FPI) with relatively low finesse.

As the outer layer is displaced gradually from the equidistant position and a propagating “defect mode” \([15–17]\) is induced inside the PhC, the associated resonant transmission peak depicted in Figs. 4(a) and 4(b) sweeps across the photonic band gap, similar to tuning the peak transmission frequency \(\nu_m\) in a scanning FPI according to the resonance condition \(\nu_m = m / c = 2 / l_c\), where \(l_c\) is the cavity length in vacuum and the integer \(m\) is the mode order. The latter remains unity due to a subwavelength scale \(l_c\) that supports only the excitation of a single axial mode. In this example the analogy between the defect mode and the axial FP cavity mode becomes more apparent at the central frequency that fulfills the QWS condition in an unperturbed PhC. Because of the relatively low finesse values, typically needed for the described outcoupler mode, the fractional width of the transmission peak (or the reflectivity dip) \(\Delta \nu_T / \nu_C \sim 10^{-1}\) shown in Fig. 4(a) turns out to be much broader than the bandwidth of the generated THz FEL pulses which has the order of \(\sim 10^{-3}\) (indicated by the dashed line). All frequencies within the FEL bandwidth experience then a nearly constant outcoupling ratio as is the case for metallic hole outcoupler mirrors.

In order to introduce an extra degree of freedom for achieving the desired coupling ratio with the proper tuning rate, additional parameters of 1D PhC can be exploited. Methods such as combination of dielectric materials in composing the PhC structure \([13]\) (i.e. refractive index variation), tilting of the outer dielectric layer a few degrees as illustrated in I.b, and creating a pair of nested (coupled) PhC cavities with individually adjustable outmost layers \([12,13]\), as displayed in I.c, can be utilized to overcome the limitations posed by a single variable parameter in establishing the proper relation between coupling ratio and tuning rate.

**FIG. 3.** (Color) Dynamic reflectivity/transmission tuning schemes. The labels above refer in the text to the respective stacking configurations.

**FIG. 4.** (Color) Transmission peaks within the reflectivity band vs defect layer thickness. In (a) the outermost quartz wafer of a four layer stack with the sequence \((3 + 1)\) is displaced from the equidistant position (75 \(\mu m\)) while in (b) the center defect layer is surrounded by two-layer stacks \((2 + 2)\). In the latter case the fractional bandwidth of the associated transmission peak amounts to \(\Delta \nu_T / \nu_C \sim 3.5 \times 10^{-2}\).
Defects implemented in the PhC structures shown in II.a and II.b (Fig. 3) cause, on the other hand, steep changes of reflectivity (i.e. narrow transmission bands) within the photonic band gap. The PhC structures of this group correspond to thin high-$Q$ cavities involving two highly reflective mirrors separated by the defect layer. The attained high finesse values give rise to sharp transmission peaks as displayed in Fig. 4(b) where the reflectance spectra results from the insertion of defects of the type illustrated in II.a. Adding more periods on both side of the defect and using also (low loss) dielectrics with the highest refractive index contrast leads to extremely narrow transmission bandwidths and high-$Q$ factors. In Si based PhCs, which exhibit the highest index of refraction ratio considered here, $Q$ values of several thousands and several tens of percentage change in transmission due to a fraction of a micron displacement can be readily achieved by a few cells stacked at each side of the defect. These PhC structures can act as narrow-band filters as well as THz modulators [in combination with fast piezoelectric transducers (PZT)] that are frequency tunable within the photonic band gap.

Finally, the PhC type illustrated in III (Fig. 3) allows one to vary the unit cell size while equidistant spacing is preserved. This feature helps to extend the THz FEL mirror’s high reflectivity range significantly by shifting the photonic band gap center towards lower (or higher) THz frequencies [13].

III. SIMULATION AND EXPERIMENTAL RESULTS

In the following simulation and experimental results are presented that demonstrate the applicability of the proposed and implemented tuning mechanisms using 1D PhC mirrors. The transmission/reflection characteristics of these structures are computed using the transfer matrix method. The incident THz fields are assumed to be (1D) plane waves traveling along the longitudinal axis that is normal to the layer interfaces. Measurements of transmission spectra are carried out at BESSYII storage ring in conjunction with a high performance Fourier-transform infrared (FTIR) spectrometer (Bruker IFS 125HR) and a liquid helium-cooled Si bolometer (IR Labs). A Hg arc lamp (100–40 cm$^{-1}$) and the THz coherent synchrotron radiation (CSR) pulses generated by the $\alpha$ mode of the storage ring served as the FIR source. In the latter case, the storage ring generates intense, stable broadband CSR pulses in the frequency range from 5 to 40 cm$^{-1}$ [18]. Transmission spectra are obtained operating the spectrometer under high vacuum. Reflectance spectra is deduced from the measured transmission spectra by taking into account the spectral properties of crystalline quartz’s complex index of refraction [6,8]. Throughout the measurements a spectral resolution of 1–2 cm$^{-1}$ is employed that is sufficient to characterize tuning properties of the outcoupler/high reflectivity PhC mirrors with the proper resolution. The FTIR spectral resolution is increased by a factor of 10 for the transmission measurement of a relatively narrow-band, high-$Q$ transmission filter described in Sec. III.D.

A. Test PhC mirror design

In our preliminary study, which aimed at testing the performance of the proposed schemes, z-cut (for minimized birefringence) crystalline quartz was preferred over silicon due to relative ease in handling the quartz wafers, its transparency in the visible region allowing easy alignment of the PhC mirrors and due to lower manufacturing costs. A batch of 20, double-side (optical quality) polished z-cut crystalline quartz wafers were obtained from Valley Design. Thicknesses of the individual wafers (etalons) were measured by employing a Bruker IFS 66v/s FTIR to be 32 ± 2 μm (rms). In view of the fact that most of the operational or planned THz FELs employ parallel plate waveguide (PPW) cavities with 10 mm or less plate separation, a wafer height of 15 mm was found to be adequate for the construction of a robust and mechanically stable PhC mirror assembly. In the lateral, the single wafer dimension can be extended up to 45 mm (for the mentioned wafer thickness and tolerances) to meet design requirements of relatively lengthy rf-linac based THz FEL resonators. Vacuum gaps are formed by spacers made of mylar.
films with the same thickness deviation as for the quartz wafers. The layer assembly is enclosed between a metallic frame and a stiff, flat polished plate. Apertures centered on both pieces allow the incident radiation to propagate through the layer stack. The upper plate is tightened using small screws, exerting evenly distributed pressure on the wafer surfaces with the help of rubber strings attached to it. In the preliminary design, vacuum gap variations are first accomplished in discrete steps by employing mylar films of various gauges. In addition, continuously tunable defects are generated by means of a high-resolution stepper motor driven holder structure which accommodates the outmost layer (or bilayers), as indicated by the $3+1$ sequence in Fig. 3-Ia.

An advanced design of current interest in our work that enables individually adjustable interlayer spacing is shown in Fig. 5. Here, the cylindrically shaped layer surfaces provide the necessary focusing of the intracavity radiation fields in the horizontal plane [14]. The radius of curvature of the mirror surfaces amounts typically to several meters.

The appeal of this design lies in the fact that the approach leads to a versatile reconfigurable, multifunctional PhC mirror which combines the features of dynamically variable outcoupling with either tunable bandpass filtering or the above-mentioned band shifting on a single, compact device that can be used to great effect in manipulating the FEL dynamics and the resulting spectral properties of the generated THz radiation. Nonetheless, the less complex, hence somewhat more robust PhC mirror approach that relies on a single actuator (or PZT transducer) as represented in Figs. 3-I and 3-II, maintains a number of the crucial tuning features and will be the focus of the presented results below.

B. Dynamical reflectivity tuning

The central wavelength $\lambda_C$ of the high reflectivity bands shown in Figs. 6(a) and 6(b) is set at around $270 \, \mu m$ for a four and a five layer PhC mirror by assembling $31 \pm 2 \, \mu m$ thick quartz wafers separated by $67 \pm 2 \, \mu m$ vacuum gaps. The corresponding reflectivity maxima of 0.988 and 0.997

![Graphs showing reflectance and transmittance spectra](image)

FIG. 6. (Color) Numerically calculated reflectance (dashed line) and reflectance (solid line) obtained from the measured transmittance spectra are depicted for the four layer (a) and the five layer (b) quartz PhC. The respective transmittance spectra around the band gap center are shown in (c) and (d). The asymmetric behavior present in (d) is due to a small defect arising from an imperfection in one of the quartz layers. The transmittance data of each plot is recorded with 2 cm$^{-1}$ spectral resolution and averaged over 160 samplings.
agree closely, within ±0.1%, with the computed ones. The achieved measurement accuracy is better than this value at the used spectral resolution [Figs. 6(c) and 6(d)]; the observed small discrepancy can be also attributed to deviations of the complex index of refraction assumed in the predictions from the actual ones. The constructed test PhC mirrors, which feature a nearly perfect periodicity, serve as the starting point for experiments to demonstrate the dynamical reflectivity tuning concept. Experimental data plotted in Fig. 7(a) contrast the reflectance spectra of the (ideal) four layer PhC mirror (blue solid curve) with the spectra generated in response to the insertion of defects (outer layer displacements and tilt). The presented sample case demonstrates the tuning capability by controlling not only the position of the reflectance minima at a given wavelength but also its amplitude. The dotted lines seen in Fig. 7(a) signify the targeted range of the outcoupling ratio. One can observe that the minima of the reflectivity dip at around the desired wavelength (∼300 μm) turns out to drop below the targeted range by tuning only the defect layer’s thickness (indicated by an arrow). By making use of an additional variable parameter (in this case by rotating the outmost quartz wafer a few degrees around the horizontal axis, as mentioned before), the minima is adjusted to the desired level while keeping its abscissa fixed [see green dashed curve in Fig. 7(a)]. Subsequent fine-tuning for a final optimization of the outcoupling ratio is carried out by positioning the outmost quartz wafer in micron steps at around the “coarsely” adjusted defect layer thickness [see Fig. 7(b)]. The induced change in reflectivity (transmissivity) at a fixed wavelength of ∼300 μm vs wafer displacement is shown in the inset. Here the smallest tuning rate monitored was less than 0.03%/micron (averaged value over a scan length of 10 microns at the vicinity of the reflectivity minima).

On the other hand, Fig. 8 displays the effect of using refractive index variation in two different defect layer configurations (3 + 1 and 3 + 2) as a means of introducing the additional degree of freedom. Here, the induced reflectivity change results from the displacement of the control wafer(s) with respect to the minima position at a fixed λ ∼300 μm. Either single or multiple quartz wafers in the stack are replaced by the ones made of CVD diamond (D). Exhibiting a higher refractive index ratio, the diamond wafer (same is valid for Si wafer) enhances the resonant transmission, hence the amplitude of the reflectivity dip and invokes an opposite effect to the one induced by tilting

![Figure 7](image7.png)

**FIG. 7.** (Color) (a) Measured transmission peaks created by displacing and subsequent tilting (arrow) the outermost quartz wafer (3 + 1). Fine-tuning of the outcoupling ratio is demonstrated in (b) at around 300 μm by employing a HR stepper motor driven actuator. Inset: reflectance changes obtained at a fixed wavelength (dashed line) of ∼300 μm as a function of the scan length.

![Figure 8](image8.png)

**FIG. 8.** (Color) Refractive index variation provides a large tuning range for setting the amplitude of the reflectivity dip at the vicinity of any THz-FEL outcoupling ratio of practical relevance. The solid curve refers to the “all quartz 3 + 1” sequence.
the control wafer. Note that, unlike other tuning schemes proposed in the study, wafer tilting has the drawback of generating a loss channel for the fundamental mode excited within the waveguided cavity; the associated decrease in the coupler efficiency, however, does not exceed a few percentages.

In terms of generating the two complementary effects mentioned above that are counteracting each other, the scheme presented in Fig. 5, which incorporates independently adjustable (outmost) layers, constitutes a more elegant way of implementing the desired flexible tuning capability. Using what we call here a nested (coupled) PhC cavity, at least 2 degrees of freedom are made available in manipulating the layer defects, influencing thereby interference characteristics of the multilayer structure such that the reflectance value and its slope can be controlled independently (in particular position and amplitude of the reflectance minima) at a given wavelength within the high reflectivity band. This is illustrated in Fig. 9, using a four quartz layer stack, at two different wavelengths by either increasing or reducing the value of the reflectance minima at a fixed operational wavelength. Nested PhC cavities can be also built of composite low-loss dielectrics in order to extend further the tuning capability of the PhC mirror by integrating the effect of refractive index variation, as described before.

It should be pointed out here that in the specific sample case described in Figs. 7(a) and 7(b), which was taken from a THz FEL design study [3], in view of the relatively large bandwidths of the generated transmission peaks and the associated low slope values, it suffices in practice to manipulate simply a single parameter, namely, the outmost defect layer’s thickness, in order to cover the envisaged range of outcoupling ratios across the entire photonic band gap. In general, however, a more sophisticated multiparameter adjustment scheme, as described above, might be necessary to meet specific requirements imposed by a FEL design.

C. Photonic band gap shifting

The central wavelength of the photonic band gap relates to the period of the PhCs employed here as $\lambda_C = \lambda_{PC} \cdot \frac{4n_d}{n_d + 1}$. A spectral shift of $\lambda_C$ and the respective band gap can be achieved (using the same PhC mirror and dielectric wafers) by increasing (or decreasing) the vacuum layer thickness as illustrated in Fig. 3-III). This is verified experimentally by altering the unit cell period in the five quartz layer PhC, described before [see Fig. 6(b)]. Figure 10(a) displays the measured reflectance spectra of

![Figure 9](image1.png)

**FIG. 9.** (Color) Dashed curves represent the reflectivity minima generated by the $3+1$ configuration. Note that the latter controls only position of the reflectivity dip but not its amplitude. This task can be accomplished by using the nested PhC cavity.

![Figure 10](image2.png)

**FIG. 10.** (Color) Shifting high reflectivity bands as a means of extending the operational spectral range. In (a) measured and computed bands of a five layer ($\sim 31 \mu m$ thick) quartz stack. In (b) calculated spectra of a four layer $23 \mu m$ thick Si wafer stack. Vacuum spacings: 75, 105, and 135 $\mu m$, respectively.
both PhCs with $\lambda_{PC}$ being set to 100 and 135 $\mu$m, respectively. The measured maximum reflectance (99.7%) remains constant within $\pm 0.1\%$, noting that the altered PhC structure does not comply with the QWS condition anymore. A further increase in the gap separation up to 132 $\mu$m, i.e. $\lambda_{PC} \sim 200 \mu$m (that had to be carried out in the preliminary design in discrete steps) led to periodicity problems arising from the relatively thick (and rigid) mylar spacers used. Figure 10(b) shows the computed band shifts achieved by employing four layer Si stacks separated by similar gap spacings as implemented in the above described quartz PhC mirror. As the shifted central wavelength increases according to the above given relation, the respective bandwidth broadens following roughly the relation given in Eq. (1). Estimations backed by the agreement obtained with the experimental data point at more than doubled operational spectral ranges (due to extensions including shifts to lower and higher frequencies) by employing a variable gap PhC mirror while the reflectance band maxima is maintained.

The practical relevance of band shifting that is ideally implemented in the scheme displayed in Fig. 5 is twofold. The continuous tunability offered by the currently planned and operational THz FELs over a large spectral range (typically covering 100 to 10 cm$^{-1}$) necessitates a broadband feedback and outcoupling mechanism. To this purpose, only a few variable gap PhC mirrors (with the respective dielectric layer thicknesses) suffice to cover the entire operational range, matching practically the broadband characteristics of widely used metallic mirrors. However, unlike the latter, variable gap PhC mirrors exhibit an exceptionally high outcoupling efficiency of nearly 100% combined with capabilities of FEL power output optimization at any operational wavelength as well as dynamically tunable narrow-band filtering. The second benefit of band shifting concerns the improvements that help to enhance the mechanical stability of the PhC mirror. In view of the relatively thin layers involved in covering particularly the short wavelength range 300 $\mu$m and below, a significant increase of layer thicknesses can be achieved by employing higher (odd) harmonic photonic band gaps, instead of the fundamental. This implies usually a trade-off between the extent of high reflectivity bands and the layer thicknesses used, as illustrated in Fig. 11. Here, fundamental bandwidth is contrasted with the third harmonic reflectivity band of a PhC mirror that is assembled by stacking 3 times thicker dielectric wafers while holding the initial gap spacing fixed. Variable gap PhCs enabling band shifting help in this case to recover the portions of the high reflectivity band that were given up otherwise for the sake of an enhanced structural stability.

**D. Intracavity modulators (filters) for THz FELs**

In addition to the above presented features, that have been in large verified experimentally through the built test pieces, PhC mirrors with adjustable vacuum defect layers can be configured to function as tunable THz filters as well as modulators. Various approaches have been pursued to engineer tunable (electrically, magnetically, or by an external laser source optically controlled) THz filters as well as modulators/switches by using 1D and 2D PhCs [19–28]. Most notably from those approaches for the here envisaged THz FEL applications is the group which employs liquid crystals (LC) in conjunction with dielectric layers [26,27]. In fact the combination of both, individually tunable vacuum defect layers with electrically/magnetically controlled LC fillings, would enable new intriguing techniques in manipulating the temporal/spectral characteristics of the FEL buildup process. The latter approach, however, suffers

![FIG. 11. (Color) Third harmonic band centers are shifted towards shorter or longer wavelengths by varying the spacing (initially 75 $\mu$m) between each quartz layer (110 $\mu$m thick) in (a) and Si layer (70 $\mu$m thick) in (b). Note that the respective fundamental HR band (not shown here) of the third harmonic band gap extends from ~800 $\mu$m to well over 1000 $\mu$m for the Q PhC (~750–1300 $\mu$m for the Si PhC).](image-url)
sively well the predicted value for the 2 + 2 stack. The bandwidth is reduced further down to $9 \times 10^{-3}$ using the 3 + 3 configuration. In (b), 3Q + 3Q shows the corresponding change in transmission that is induced by varying the center vacuum defect layer and keeping the wavelength fixed. In contrast, Si PhC provides an order of magnitude larger transmission gradients with the same number of cells assembled in the stack 3Si + 3Si ($\Delta \nu_T/\nu_C \sim 4 \times 10^{-4}$).

the use of quartz that inherently exhibits piezoelectric properties.

IV. CONCLUSION

The use of 1D PhCs as nearly 100% efficient, reflectivity tunable, broadband couplers is a novel concept towards achieving significant improvements in the performance of THz FELs and the related high-$Q$ THz pulse stacker cavities. The developed scheme relies on controlling/manipu-
lating the optical properties of an FEL mirror through dynamically adjustable and versatile reconfigurable vacuum defects created inside a 1D PhC structure. While simple to implement, it is capable of addressing critical design requirements imposed by the high intracavity power levels as well as relatively large cavity-mode cross sections (many cm²) inherent to long wavelength (rf linac or electrostatic accelerator based) THz FEL resonators. A variety of techniques [refractive index variation, nested (coupled) PhC cavities, photonic band gap shifting] are presented in the work that extend the operational capabilities of the investigated PhC coupler mirrors along with their spectral range. The use of higher harmonics in conjunction with the photonic band gap shifting constitutes a practical means to enhance the PhC’s structural stability while maintaining in large functionality of the fundamental band gap. In addition to the exceptional coupler/high reflectivity characteristics, the scheme enables the implementation of tunable, narrow-band intracavity filters as well as fast modulators in THz FELs. These components can be naturally imbedded in the presented PhC mirror scheme in order to influence the FEL dynamics and to manipulate the temporal/spectral characteristics of the generated intense THz pulses. The performance of the tested PhC mirrors was crucial in verifying the computed concept and identifying the necessary improvements in the design. The next step, the practical realization of the studied PhC schemes in a THz FEL device, will demonstrate the final proof of feasibility under real life conditions.

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