TMD Presentation

Rebecca Seviour
*University of Huddersfield*
\[ a \approx \lambda \]

\[ a \ll \lambda \]
lattice, as shown in figure 4.1.

Figure 4.1: 2D triangular PC lattice with a defect.

Considering a finite lattice, where the top and bottom of the lattice shown in figure 4.1 are covered by metal plates, the defect region becomes an enclosed space where EM waves can be excited. EM waves confine in the defect region see the surrounding global lattice, which presents bands and gaps only for TM polarised waves according to figure 2.6. Therefore, only the TM waves at frequencies inside the band gap can be confined in the defect, other TM waves and all the TE waves are not able to be confined, but propagate through the lattice, as they are in the propagation bands of the lattice.

According to this frequency-selective property, PCs bring the opportunity to make mode-control resonators that only hold specific resonant states. This is an advantage over the conventional pillbox cavities, as a pillbox cavity with fully enclosed boundary confines all the resonances formed by both TE and TM polarised waves. In the application to RF generation, only the TM01-like (or monopole-like) resonance state is needed, which is similar to E. I. Smirnova’s application to particle accelerators [4, 42]. E. I. Smirnova examined a metallic PC with a triangular lattice and a single site defect (figure 4.2 (a)), and found that by having the rod radius-spacing ratio $r/a$ between 0.1 and 0.2, only a TM01-like state was confined.
Considering a finite lattice, where the top and bottom of the lattice shown in figure 4.1 are covered by metal plates, the defect region becomes an enclosed space where EM waves can be excited. EM waves confine in the defect region, see the surrounding global lattice, which presents band gap(s) only for TM polarised waves according to figure 2.6. Therefore, only the TM waves at frequencies inside the band gap can be confined in the defect, other TM waves and all the TE waves are not able to be confined, but propagate through the lattice, as they are in the propagation bands of the lattice.

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Applications of the theory illustrated by figure 4.2 were further verified by Eigenmode simulations using Finite-Element-Method (FEM) codes, such as COMSOL [76]. The profiles of the monopole and dipole resonance states/modes in a PC resonator of \( r/a = 0.16 \) and an equivalent pillbox cavity from COMSOL 2D Eigenmode simulation are presented in figure 4.3, which shows the higher-order states are not confined any more but propagate away from the lattice, making the PC resonator only support the monopole-like state.
Experimental - Numerical Verification

<table>
<thead>
<tr>
<th></th>
<th>HFSS results</th>
<th>Measurement results</th>
</tr>
</thead>
<tbody>
<tr>
<td>input PC, $f_{0,in}$ (GHz)</td>
<td>9.54234</td>
<td>9.5422</td>
</tr>
<tr>
<td>output PC, $f_{0,out}$ (GHz)</td>
<td>9.53987</td>
<td>9.5379</td>
</tr>
</tbody>
</table>

Figure 4.20: Measurement system setup using Agilent E8362B vector network analyser. Figure 4.23: Frequency response and state selectivity of the input and output PCs. Figure 5.28: Measured reflection and power leakage at 9.532 GHz.
The energy exchanged from the electron bunches to the EM field excited by the modulated beam in the EL defect was significantly limited by the low beam current. Hence the strength of the beam profiles, axial velocity modulation and charge density distribution at saturation. The module and experimental system setup. (b) Spectrum of output signal excited by velocity-modulated beam dynamics: (a) beam profile, velocity and charge density distribution; (b) beam transverse phase-space plots at points A, B, C and D. Figure 5. Proof-of-principle experimental setup and results. (a) The two-PC klystron/Accelerator of Basic Sciences under Contract No. W-31-109-ENG-555. * Work supported by U.S. Department of Energy, Office of Basic Energy Sciences.

In the APS linac klystron amplifiers, the connectors couple to the waveguide in the form of waveguide higher-order modes above cutoff. A damper design of similar function is used on a narrow wall of the rectangular waveguide for damping klystron harmonics while decoupling the dominant TE01 mode. The rf power reflected some power without delivering power to the load cavity structure that works as a matched load. However, since the accelerating cavity is a narrowband load, the harmonic frequency power caused some problem with decoupling the harmonics was not very effective. Even though more effective rf shielding may be possible, it was not desirable for quality vacuum pumping. The tube to the ion pump is connected to the high-voltage connection to the ion pump. The metallic tube to the ion pump passes the higher TE01 frequency in dominent TE01 mode but also in higher-order waveguide modes. Computer simulations are made to investigate the waveguide harmonic damping characteristics of the damper. The rf power in the output cavity of the klystron amplifier may couple to the waveguide in the form of waveguide harmonic frequency power. In order to eliminate the pump has a cutoff frequency higher than the fundamental klystron frequency, but the harmonic spectrum may form standing wave resonances in the waveguide higher-order modes above cutoff. Computer simulations are made to investigate the waveguide harmonic damping characteristics of the damper.
A waveguide harmonic damper was designed for removing the harmonic frequency power from the klystron amplifiers of the APS linac. Straight coaxial probe antennas are used in a rectangular waveguide to form a damper. A linear array of the probe antennas is used on a narrow wall of the rectangular waveguide for damping klystron harmonics while decoupling the fundamental frequency in dominant TE$_{01}$ mode. The klystron harmonics can exist in the waveguide as waveguide higher-order modes above cutoff. Computer simulations are made to investigate the waveguide harmonic damping characteristics of the damper.

1. **INTRODUCTION**

In the APS linac klystron amplifiers, the connectors for the high-voltage connection to the ion pump were burned by the klystron harmonics power. The metallic tube connected to the ion pump passes the higher frequency harmonics power, and the metal screen used to decouple the harmonics was not very effective. Even though more effective rf shielding may be possible, it was not desirable for quality vacuum pumping. The tube to the pump has a cutoff frequency higher than the fundamental klystron frequency, but the harmonic spectrum power, shown in Figure 1, is not attenuated sufficiently. In the APS, five klystrons are used. Each klystron normally delivers 5-microsecond 35-MW peak power pulses to the accelerating structures. The average power of harmonic spectrum in the waveguide is estimated as several tens of watts. In order to eliminate the heating due to the harmonic power, a damping circuit is needed in the waveguide. The harmonic frequency power in the output cavity of the klystron amplifier may couple to the waveguide in the form of waveguide higher-order modes as well as the dominant mode. The klystron harmonic frequency power caused some problem in the APS storage ring, so the harmonics were damped by multiple probe antennas mounted on the narrow wall of the waveguide. A damper design of similar function is needed in the 2.856-GHz linac system. For this reason, the waveguide harmonic damper designs were studied using computer simulation.

2. **HARMONIC DAMPER**

In the waveguide transmission line, during normal operations, the fundamental frequency propagates as a travelling wave to the load cavity structure that works as a matched load. However, since the accelerating cavity structure is a narrowband load, the harmonic frequency spectrum may form standing wave resonances in the waveguide between the klystron output cavity and the cavity structure.

Figure 1. Harmonic spectrum of 2.856-GHz klystron amplifier output.

Figure 2 shows the waveguide harmonic damper design employing coaxial probe antennas. A linear array of five probe antennas is used on a narrow wall of the rectangular waveguide for damping klystron harmonics while decoupling the dominant TE$_{01}$ mode. The rf power for the accelerating structure from the klystron is transmitted in the dominant TE$_{01}$ mode. The harmonic frequencies from the klystron amplifier not only exist in the TE$_{01}$ mode but also in higher-order waveguide modes. Higher order TE$_{mn}$ and TM$_{mn}$ modes couple to the antennas if $m$=odd and do not couple to the antennas if $m$=even. The index $n$ must be nonzero for both TE and TM modes.

For the fundamental frequency, the antennas may reflect some power without delivering power to the matched load of the coaxial probes. The input matching of the damper section is important for power transmission of the fundamental frequency. Ideally, the probe antennas do not disturb the TE$_{01}$ mode at the fundamental frequency. However, actual antennas can cause some...
The stub couplers were built by inserting the SMA connectors shown in figure 4.7 into the input and output PCs, in parallel with the rods, by adjusting the lattice depths in each. In the input PC, the stub coupler replaced the rod that was 2 away from the defect centre, which made the coupler become part of the lattice. In the output PC, the stub coupler was placed beside the defect region, at 14.46 mm away from the defect centre, as a small perturbation at a weak field.

The measurements in figure 4.22 were taken when both the input and output PCs were tuned to 9.532 GHz. The measurements had very small uncertainties, which were essentially caused by the oscillations of network analyser. The measured uncertainty of frequency was ±5 kHz and that of $S_{11}$ was ±0.005, both could be ignored.

### 4.4.2 Frequency Responses and State Confinements

To verify the full frequency responses of the input and output PCs, in order to examine their performances on state selectivity, the $S_{11}$s were measured over a wide frequency range from 2 GHz to 18 GHz. The measurement results were plotted in comparison with the eigenmode simulation results from HFSS and band diagrams calculated from BandSOLVE, as shown in figures 4.23 and 4.24 for the input and output PCs respectively. All the results matched within the error ranges due to fabrication uncertainties. The measured propagation bands started respectively from 12.95 GHz and 12.94 GHz for input and output PCs, both were comparable to the computational results from BandSOLVE, 12.927 GHz and 12.969 GHz.
Figure 4.2: (a) A metallic PC resonator of triangular lattice with a defect. (b) Normalised frequencies of band gap boundaries and TM eigen-states versus \( r/a \): Black solid line shows the band gap boundaries; region under and to the right of these lines are the band gap region. Coloured dots show the TM states in the PC resonator. Coloured solid lines represent the frequencies of TM modes in a pillbox cavity of radius \( R = a - r \) [4].

Applications of the theory illustrated by figure 4.2 were further verified by Eigenmode simulations using Finite-Element-Method (FEM) codes, such as COMSOL [76]. The profiles of the monopole and dipole resonance states/modes in a PC resonator of \( r/a = 0 \) and an equivalent pillbox cavity from COMSOL 2D Eigenmode simulation are presented in figure 4.3, which show the pillbox cavity.

Table 4.1 indicates that in this case the degenerate state doesn’t exist, as there is no coupled defect (gap) to present the state degeneracy.

Comparing to the results in tables 4.1 and 4.2, in both the input and output PCs the fundamental (TM010-like) states are in their band gaps with high Q.

14 GHz Lattice parameters

\[
\frac{r}{a} \approx 0.15 \quad \rightarrow \quad \frac{2.55}{c} = \frac{w a}{c} \\
\rightarrow \quad a = 8.67 \text{ mm} \\
\rightarrow \quad r = 1.3 \text{ mm}
\]
Therefore, 6 rows of rods were considered to be well ordered of the order of $10^3$, which is much higher than the Ohmic Q-factor of the order of $10^5$. In fact, the full lattice was set to have 6 rows of rods around the defects. Notice that figure 6.2 (a)-(f) present only the region not localised in the defects. All other states are in the propagation band and are differently among the degenerate states, which split each other. The dipole-like and quadrupole-like states are degenerate, which split each other. The dipole-like (figure 6.2 (b) and (c)), quadrupole-like (figure 6.2 (d)), sextupole-like (figure 6.2 (f)), ranged from the lowest frequency to $14.734 \text{ GHz}$. The results are shown in figure 6.2. Comsol 2D eigenmode simulation.

### Resonant States

- **Monopole**: 14 GHz
- **Dipole**: 14.229 GHz, 14.230 GHz
- **Quad**: 14.733 GHz, 14.734 GHz
- **Sextupole**: 15.011 GHz
Multi-defect lattice

Figure 6.2 shows that the 6-defect PC presents 4 resonant states: monopole-like (figure 6.2 (a)), dipole-like (figure 6.2 (b) and (c)), quadrupole-like (figure 6.2 (d)), and sextupole-like (figure 6.2 (f)). The dipole-like and quadrupole-like states are degenerate, which split each other among the defects. According to E. I. Smirnova’s research in [42], 3 rows of rods can produce the effect of the PC rod radius for EM reactive Q-factor of the order of 10 higher. The dipole-like and quadrupole-like states are degenerate, which split each other among the defects. Notice that figure 6.2 (a)-(f) present only the regime of the propagation band, (b) unconfined higher-order state and (c) confined higher-order state.

Equation (6.16) indicates that in the 6 resonant states for a given order \( n \) of the defect, the spatial frequency \( \omega / 2 \pi c = a / \lambda \) is calculated to be

\[
\beta_n = \frac{n}{r/a}, \quad n = 1, 2, 3, \ldots
\]

where \( \beta_n \) is the resonance frequency of the \( n \)-th resonant state in the 6-defect PC: (a) resonant states and propagation band, (b) unconfined higher-order state and (c) confined higher-order state.

In fact the full lattice was set to have 6 rows of rods around the defects. All other states are in the propagation band and are not localised in the vicinity of the defects.
the filling-up time, to provide a higher acceleration gradient. Therefore, instead of the two-PC system shown in figure 6.27, a multi-PC (with several intermediate PCs between the input and output PCs) system may be necessary to improve the gain.

For a system driven to the saturation condition by electron beams of $V_0 = 200$ kV, a high acceleration gradient of 32 MV/m can be obtained. This gradient is associated with a peak surface electric field 46.8 MV/m around the central beam hole edge (figure 6.29 (a)) and a peak surface magnetic field 120.2 kA/m at the inner sides of the inner-most rods (figure 6.29 (b)), shown by HFSS eigenmode simulation.

Figure 6.29: Distributions of (a) electric field and (b) magnetic field at the inner surface of the 7-defect PC.

Experimental studies of breakdown in the 7-defect PC are beyond the scope of this thesis. However, it is worth pointing out at this stage that according to the investigation presented in [102], breakdowns in single defect metallic PCs are dominated by the large pulsed heating produced by the high surface magnetic fields at the inner edge of the inner-most rods. The 7-defect PC has a peak magnetic-electric field ratio of 0.00218 A/V, which is significantly lower than the field ratio 0.00429 A/V for the PC acceleration structure presented in [102]. This indicates that the breakdown in the 7-defect PC is less dominated by the peak surface magnetic field. Experimental investigations of breakdown, together with transient response of fields in the 7-defect PC are expected in future research.

6 inputs 200 KV each

Peak E-field = 46 MV/m

Peak B-field = 120 KA/m
In this case the FFT spectrum presented only the monopole-like and sextupole-like states.

Figure 6.10: The FFT of the axial electric fields excited by one of the 6 defects.

Figure 6.9: The FFT of the axial electric fields excited by one in the FFT spectrum.

Therefore, to further effectively excited.

Resonant states can consequently excited.

Excitation of all defect, 1% disorder in phase in each defect
Therefore 6 rows of rods were considered to be well ordered of the order of $10^3$. In fact the full lattice was set to have 6 rows of rods around the defects. Notice that figure 6.2 (a)-(f) present only the regular states: monopole-like (figure 6.2 (d)), dipole-like degenerate states, (c) and (f); quadrupole-like (figure 6.2 (e)), and sextupole-like state. Figure 6.2 shows that the 6-defect PC presents 4 resonant states, which split each other. The dipole-like and quadrupole-like states are degenerate, which split each other. The dipole-like and quadrupole-like states are degenerate, which split each other. The dipole-like and quadrupole-like states are degenerate, which split each other. The dipole-like and quadrupole-like states are degenerate, which split each other. The dipole-like and quadrupole-like states are degenerate, which split each other.
Figure 6.6: Split of resonant states in the first 6 coupled-defect schemes of 6-defect PCs at $r/a = 0.1652$.

Figure 6.7: Change of coupling strengths ($\beta_1$, $\beta_2$ and $\beta_3$) between defects with $l_{bb}$ in a 6-defect metallic PC with $a = 34.5$ mm.

Significantly higher values than $\beta_2$ and $\beta_3$, which indicate that the closest neighbour defect has the most dominant coupling effects. Coupling strength between defects are very sensitive to $r/a$ and are significantly weakened by increasing $r/a$, as seen from the significant drop in all the three $\beta$ in figure 6.4.

Besides the $r/a$, another factor that affects the split of resonant states is the adjacent defect centre-to-centre spacing, which is also referred to as the adjacent electron beam centre-to-centre spacing ($l_{bb}$) for themulti-beam system presented in the next section. A 6-defect PC based on triangular lattice has discrete values for $l_{bb}$ measured in terms of $a$, according to different coupled-defect schemes. The coupled-defect schemes of 6-defect PCs based on the first 6 $l_{bb}$s: $\sqrt{3}a$, $2a$, $\sqrt{7}a$, $3a$, $2\sqrt{3}a$ and $4a$, for fixed $r/a$, are shown in figure 6.5 (a)-(f) respectively. In figure 6.5, adjacent defects are marked by a line connection from centre to centre. This makes a red hexagon in each PC, with the side length $l_{bb}$ for each case.

The splits of resonant states in the 6 metallic PCs shown in figure 6.5 were assessed in COMSOL 2D eigenmode simulations at fixed $r/a = 0.1652$. The results...
Effects of Disorder on the Frequency and Field of Photonic Crystal Cavity Resonators.. / Matthews, C.; Seviour, Rebecca.

- $a = 8.67 \text{ mm} \rightarrow \pm 80 \text{ micros}$
- $r = 1.3 \text{ mm} \rightarrow \pm 50 \text{ micros}$

$14 \text{ GHz} \sim \pm 29.7 \text{ MHz}$  
[although standard CnC has $\pm 5$ Micro accuracy]
Figure 6.16: $S_{11}$ curve and polar plot of the 6-defect PC with central rod coupler from HFSS.

The central rod coupler needs to be optimised for using in a klystron. For a klystron with high power electron beams, the coupling is largely dependent with the beam-loading effects. The presence of electron beams introduces extra power losses and hence imposes considerably low beam-loading $Q$-factors (as discussed in Section 3.4.4). Sufficiently strong electron beams can also slightly shift the resonant frequencies. Therefore, the coupling conditions can be significantly changed.

An optimised coupling with beam-loading can often be seen as over-coupled in cold tests (without the beam), which means the central rod coupled 6-defect PC can be used in a 6-beam klystron with very high perveance beams. However, for medium or low perveance beams, the over-coupled PC still needs to be tuned down to a certain extent to optimise the coupling. In this section, the coupling is still optimised without beam-loading, as a study of the tuneability of the 6-defect PC.

As the PC is strongly over-coupled, optimisation of the coupling focused on reducing the electric fields seen by the coupler, whilst maintaining the symmetry of the lattice. One efficient method to achieve this is to introduce 6 additional rods, with equal distance to the central rod coupler and lining with the inner ring of lattice rods. The radius of the additional rods ($r_s$) and the distance to the central rod coupler can be optimised.

Output Coupling

Figure 6.14: The 6-defect PC with the central rod made as coax coupler that couples to the monopole-like state.

In figure 6.14, the stub coupler equally matches each defect and hence couples to EM waves in each defect at the same time. This makes the coupler couple $135$...
Overview

- Looks promising
- Preliminary work shows coupler is feasible at 14 GHz
- good input coupling
- good stability
- with stand high voltages

To do:

- Wide lattice investigation
- Improve output coupling
- Improve modelling
- Thermal modelling
- Investigate HOM exploiting (band-width)
- Investigate fabrication techniques
  - Cold-press extruded rods into a base
  - Al mandrel, plate, acid etch away
  - hollow rod for water cooling
- Cold test
- Consider transistor integration

- way forward? [need effort (and money), phd or post-doc?]
  - STFC-case [next round may]
  - EPSRC [low probability of success]
  - TSB ?
Photonics

\[ a \sim \lambda \]

Effective-Media

\[ a \ll \lambda \]
\[
\omega = \sqrt{c^2 \left( \gamma_n - \left( \frac{\pi(2n+1)}{p} + \beta_{\text{mm}}(f) \frac{\Delta h}{p} \right) \right)^2 + \omega_c^2}
\]

\[
\gamma_n = \beta_0 \frac{p + h - \Delta h}{p} + \beta_{\text{mm}}(\omega) \frac{\Delta h}{p} + (2n + 1) \frac{\pi}{p}
\]

\[
\alpha = \left( \frac{p}{p + h - \Delta h} \right)^2
\]

\[
\beta_{\text{mm}}(\omega) = c^{-1} \sqrt{\omega^2 \epsilon_r(\omega) \mu_r(\omega) - \omega_c^2}
\]
### Lorentz's Force Equation

Time changing in $m_0c^2\gamma$ (DC and AC beam energy) is related by the $E \cdot v$ dot product in this equation. The DC beam energy $\gamma_{dc}$ is given by $(1+V_{dc}/511)$; $V_{dc}$ is the DC beam accelerating potential. While the AC beam energy exchange (stimulated emission) is related by the $E \cdot v$ dot product in this equation. The change in power between wave and beam, shows that as the accelerating potential is increased the frequency at which the gain-frequency characteristics, $\Delta P_{out}/\Delta P_{in}$ as a function of frequency at which the gain-frequency characteristics.

1st order perturbation $\gg$ Spontaneous emission

$$m_0c^2 \frac{d'}{dt} = -E$$

2nd order perturbation $\gg$ Stimulated emission

$$\langle \Delta \gamma_2 \rangle = \frac{1}{2} \frac{d'}{d} \langle \Delta \gamma_1^2 \rangle$$

$$\frac{\Delta P_{out}}{P_{in}} = -\frac{1}{2} \frac{d'}{d\gamma} \langle \Delta \gamma_1^2 \rangle m_0c^2 \frac{I}{e}$$
Dispersion relation extracted via bead pull, black dots, with the light line shown in green.

- 2 KeV/M gradient
- Redesign SRR at lower frequency to couple more effectively to slow-waves.
- Increase beam voltage (30keV -> 50Kev)
- Although CSRR breaks down @ 80W forward power

David French (Huddersfield 2013)