Implementation of a SbD-Based Synthesis Tool for WAIM-Enhanced Printed Patch Arrays

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Contents

1 Lossless WAIM Analysis

In the previous section we saw that the Reflection Coefficient is reduced by introducing materials with $Im\{\varepsilon^1\} \neq 0$. This means lossy materials, solution that we want to avoid since using lossy materials the radiation would be impossible.

In this section we will try to analyze other possible solutions, such as introducing analysis on triangular lattice and considering multi-layer WAIM optimizations.

1.1 $\varepsilon^{sub} = 12.8$ Tests

1.1.1 Test Case #3 - Single Frequency - 1 Anisotropic WAIM Layer - $\varepsilon^1 = [1 : 35] + j0$ - Triangular Lattice - $\varepsilon^{sub} = 12.8$ Tests

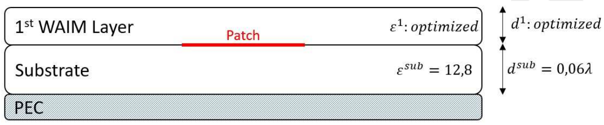


Figure 1: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.15$, $l = 0.098$ $[\lambda]$;
- Probe position: $x = 0.049$, $y = 0.0$ $[\lambda]$;
- Substrate: $\varepsilon_x = 12.8 + j0$, $\varepsilon_y = 12.8 + j0$, $\varepsilon_z = 12.8 + j0$, $d = 0.06[\lambda]$
- Floquet coefficient = 121;
- Lattice basis: $s_1 = (0.0, 0.5)$, $s_2 = (0.433, 0.25)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]\,[deg]$, $\varphi \in [0, 90]\,[deg]$, $\theta_{samples} = 182$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]\,[deg]$, $\varphi \in [-90, 90]\,[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 1$;
- Unknowns: $U = 4$;
- Unknown ranges: $\varepsilon_{xx} = [1 : 35] + j0$, $\varepsilon_{yy} = [1 : 35] + j0$, $\varepsilon_{zz} = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;

- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight= 0.4;
- Alpha= 0.4;
- Beta= 0.4;
- C1= 2.0;
- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

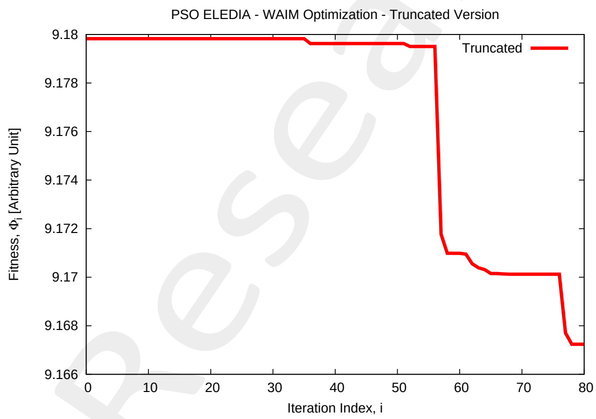


Figure 2: Fitness Dynamics.

$$Simulation\, time\, (Truncated):\ 373m\, 26s$$

$Tool$	$Optimal\, Solution$				$Fitness\, Value$	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
$Truncated$	1.00	34.25	1.00	0.033	9.180	9.167

Table 1: Optimal Solution.

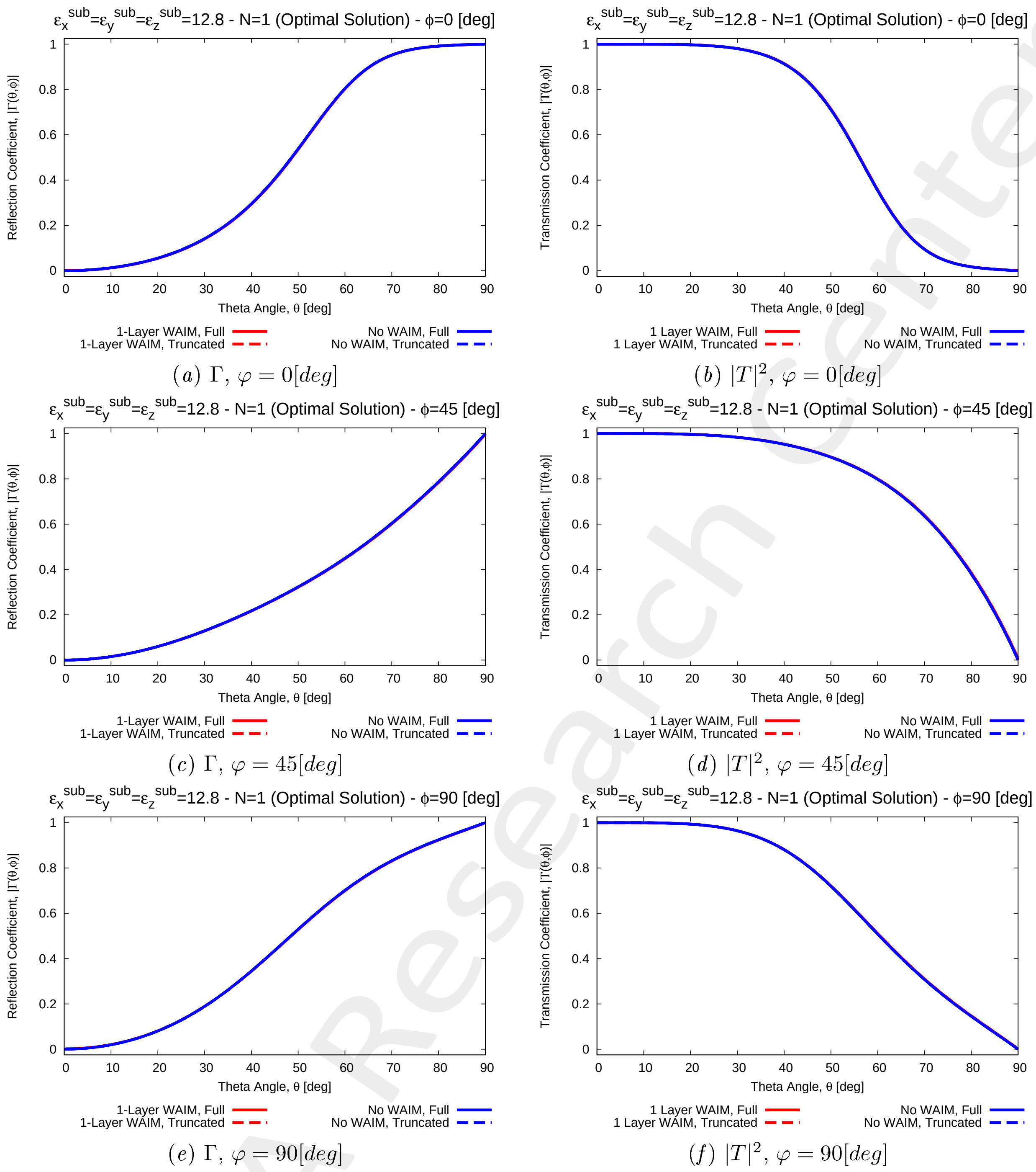
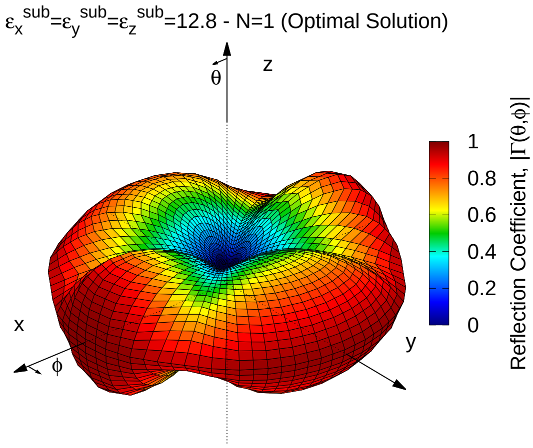
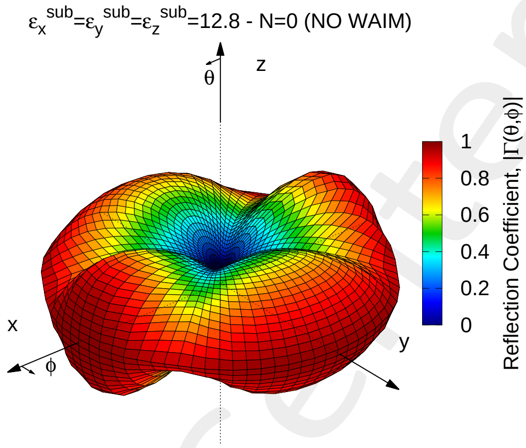


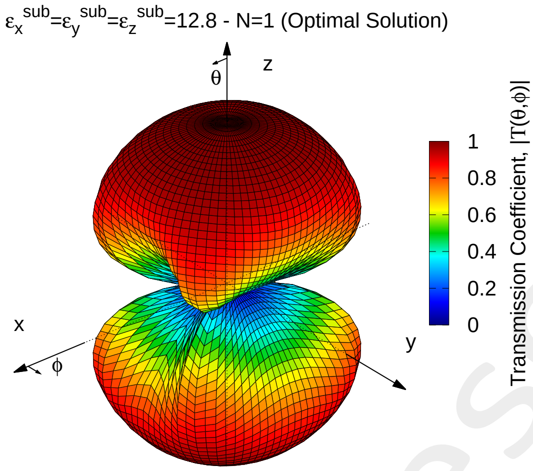
Figure 3: Reflection Coefficient along φ cuts, 1 Layer WAIM.



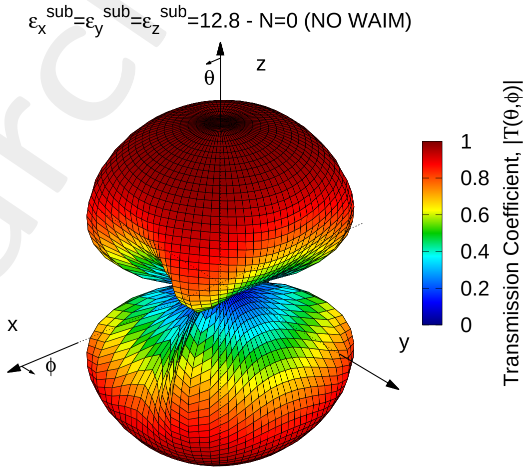
(a) Γ, 1 Layer WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 1 Layer WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 4: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	605.72	604.11	-0.27%
Truncated	605.64	604.03	-0.27%

Table 2: Cost Function Improvement.

1.1.2 Test Case #5 - Single Frequency - 2 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = [1 : 35] + j0$ - Square Lattice - $\varepsilon^{sub} = 12.8$ Tests

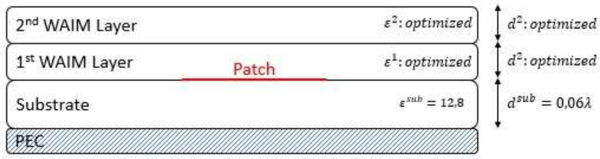


Figure 5: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.15$, $l = 0.098$ $[\lambda]$;
- Probe position: $x = 0.049$, $y = 0.0$ $[\lambda]$;
- Substrate: $\varepsilon_x = 12.8 + j0$, $\varepsilon_y = 12.8 + j0$, $\varepsilon_z = 12.8 + j0$, $d = 0.06[\lambda]$;
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.5, 0.0)$, $s_2 = (0.0, 0.5)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 2$;
- Unknowns: $U = 8$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight$= 0.4$;
- Alpha$= 0.4$;
- Beta$= 0.4$;
- C1$= 2.0$;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

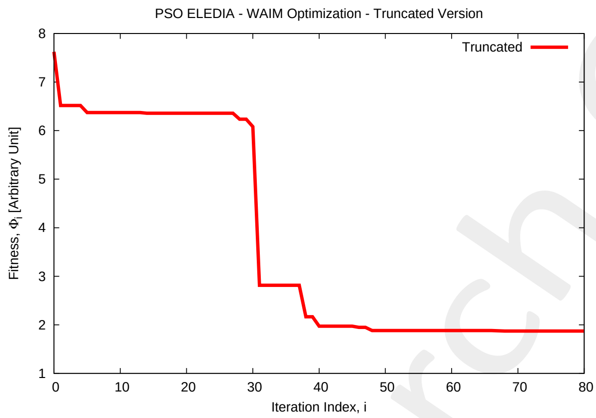


Figure 6: Fitness Dynamics.

$$Simulation\,time\,(Truncated):\ 400m\,5s$$

Tool	*Optimal Solution*								*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	20.85	17.54	20.98	0.033	33.45	18.24	19.02	0.033	7.624	1.871

Table 3: Optimal Solution.

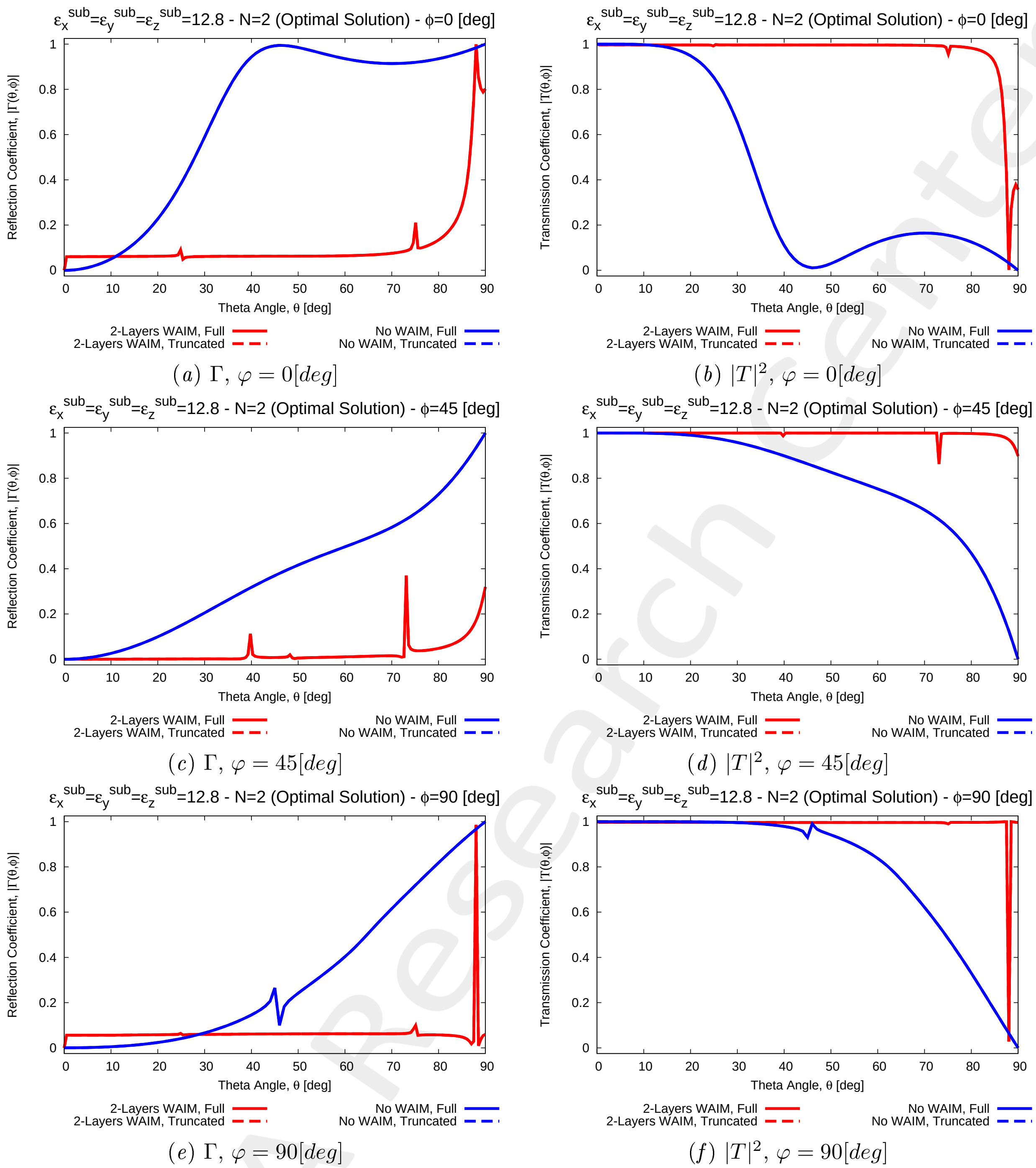
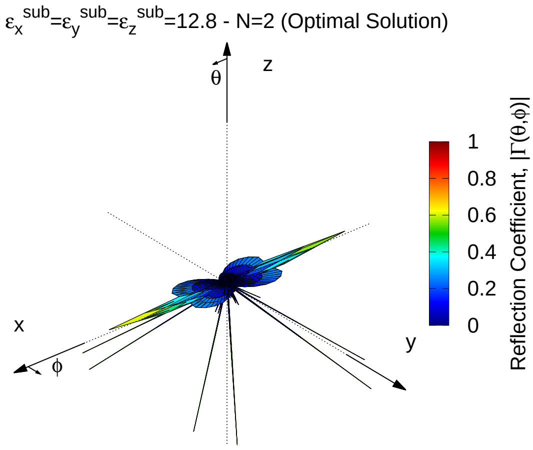
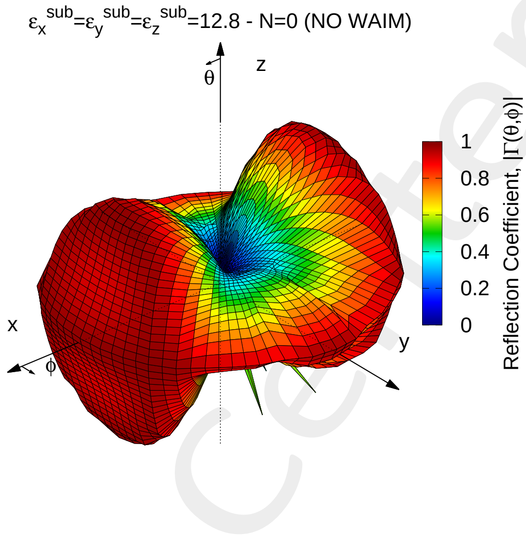


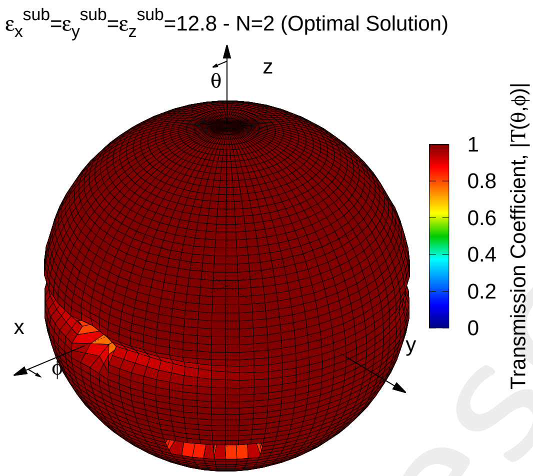
Figure 7: Reflection Coefficient along φ cuts, 2 Layers WAIM.



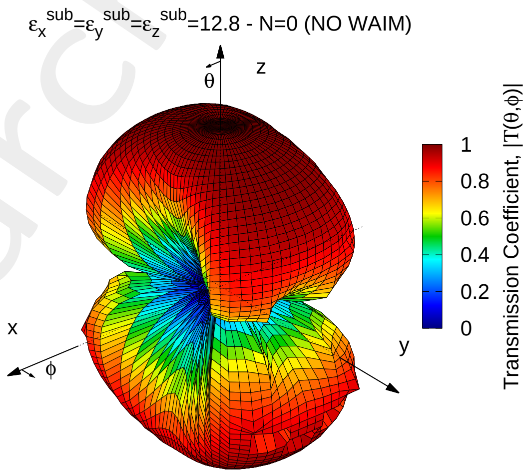
(a) Γ, 2 Layers WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 2 Layers WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 8: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	663.46	80.43	-87.88%
Truncated	663.51	80.35	-87.89%

Table 4: Cost Function Improvement.

1.1.3 Test Case #7 - Single Frequency - 2 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = [1 : 35] + j0$ - Triangular Lattice - $\varepsilon^{sub} = 12.8$ Tests

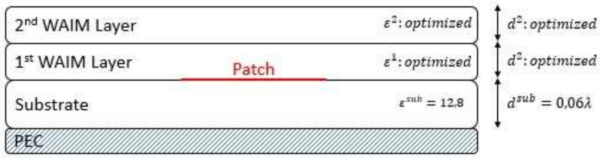


Figure 9: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.15$, $l = 0.098$ [λ];
- Probe position: $x = 0.049$, $y = 0.0$ [λ];
- Substrate: $\varepsilon_x = 12.8 + j0$, $\varepsilon_y = 12.8 + j0$, $\varepsilon_z = 12.8 + j0$, $d = 0.06[\lambda]$
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.0, 0.5)$, $s_2 = (0.433, 0.25)$ [λ];

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 2$;
- Unknowns: $U = 8$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ [λ];
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight$= 0.4$;
- Alpha$= 0.4$;
- Beta$= 0.4$;
- C1$= 2.0$;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

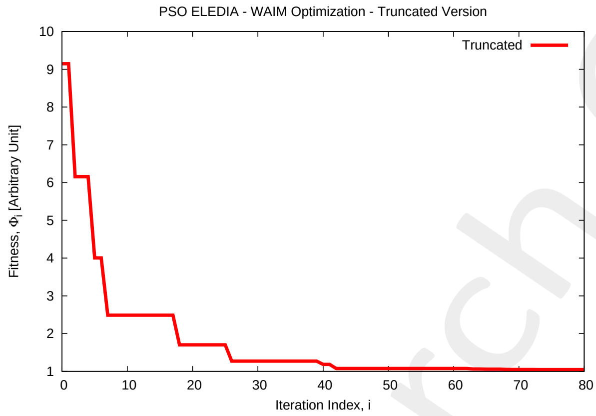
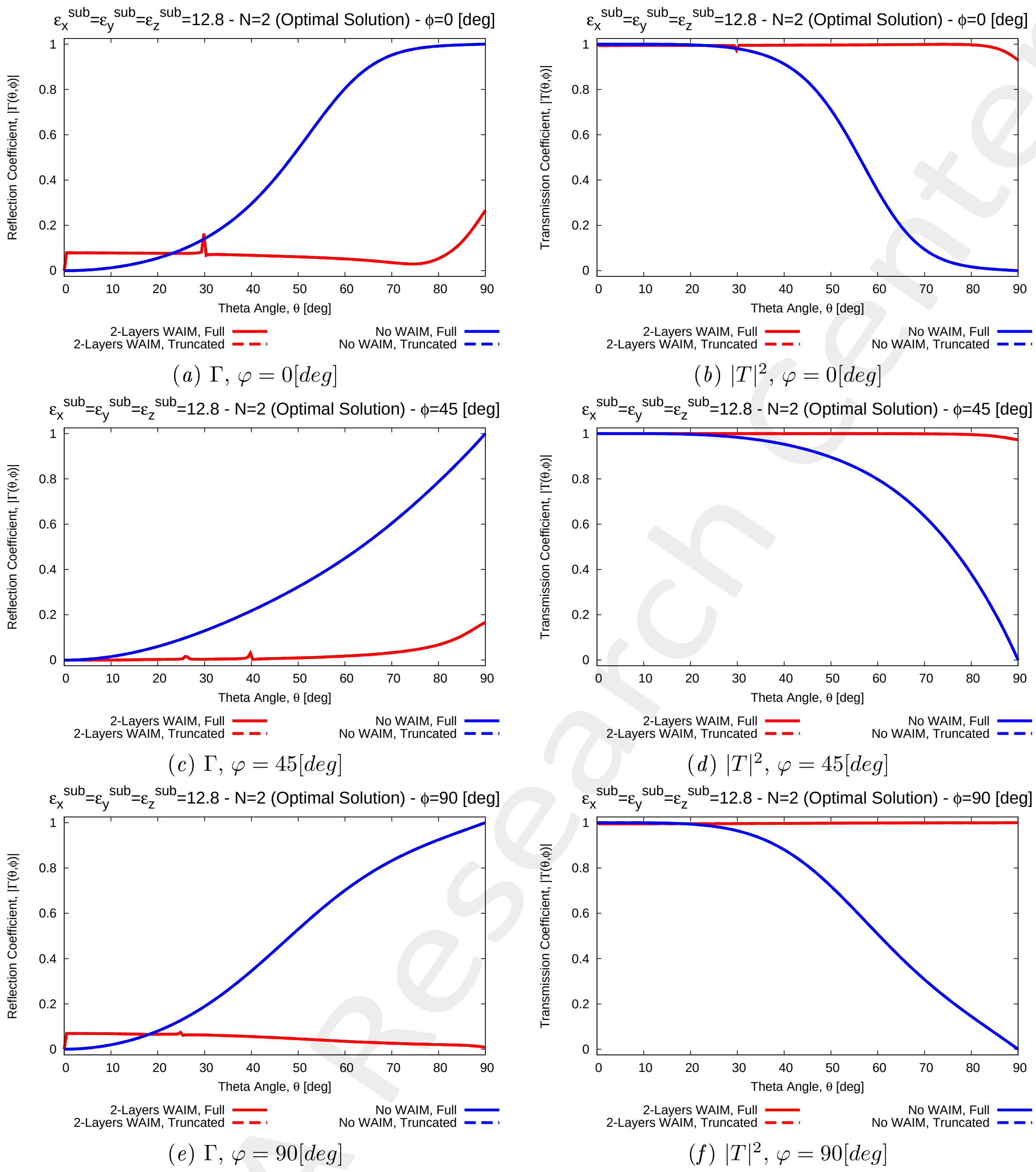


Figure 10: Fitness Dynamics.

$$Simulation\,time\,(Truncated):\ 451m\,53s$$

Tool	*Optimal Solution*								*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\,[\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\,[\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	18.51	34.75	2.25	0.037	23.89	14.52	27.46	0.048	9.148	1.047

Table 5: Optimal Solution.

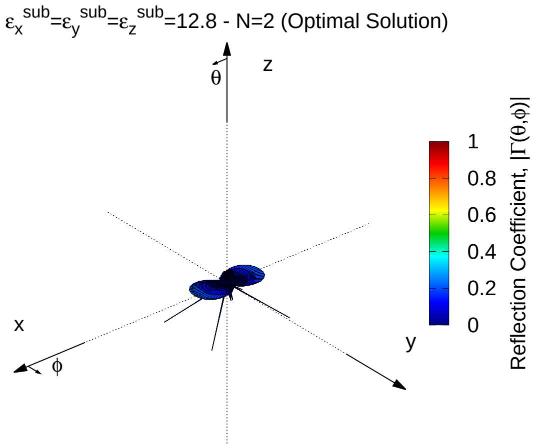


(a) Γ, $\varphi = 0[deg]$ (b) $|T|^2$, $\varphi = 0[deg]$

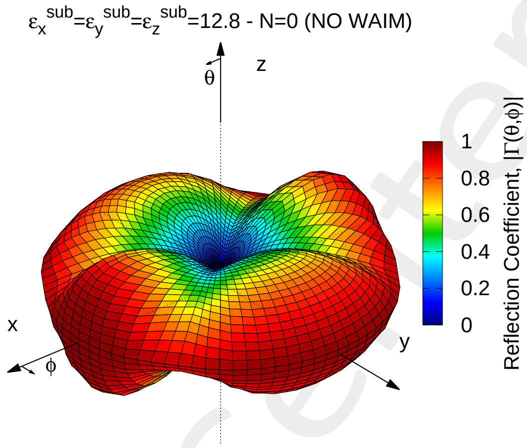
(c) Γ, $\varphi = 45[deg]$ (d) $|T|^2$, $\varphi = 45[deg]$

(e) Γ, $\varphi = 90[deg]$ (f) $|T|^2$, $\varphi = 90[deg]$

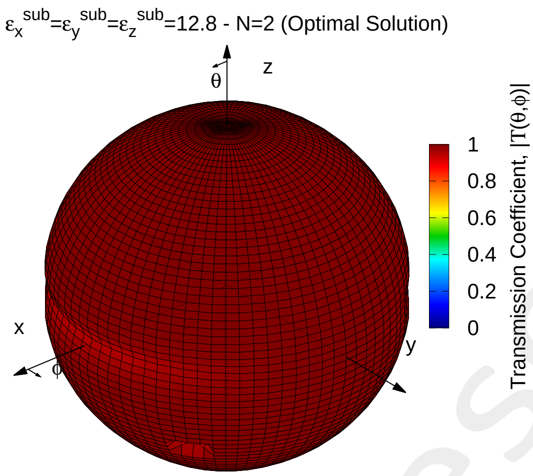
Figure 11: Reflection Coefficient along φ cuts, 2 Layers WAIM.



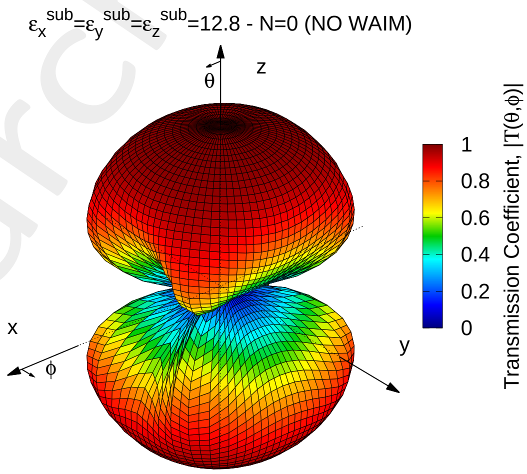
(a) Γ, 2 Layers WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 2 Layers WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 12: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	605.72	68.54	−88.69%
Truncated	605.64	68.49	−88.69%

Table 6: Cost Function Improvement.

1.1.4 Test Case #9 - Single Frequency - 3 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = \varepsilon^3 = [1 : 35] + j0$ - Square Lattice - $\varepsilon^{sub} = 12.8$ Tests

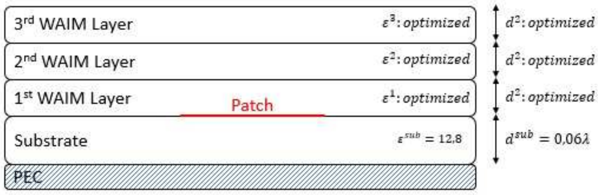


Figure 13: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.15$, $l = 0.098$ $[\lambda]$;
- Probe position: $x = 0.049$, $y = 0.0$ $[\lambda]$;
- Substrate: $\varepsilon_x = 12.8 + j0$, $\varepsilon_y = 12.8 + j0$, $\varepsilon_z = 12.8 + j0$, $d = 0.06[\lambda]$;
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.5, 0.0)$, $s_2 = (0.0, 0.5)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 3$;
- Unknowns: $U = 12$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight= 0.4;
- Alpha= 0.4;
- Beta= 0.4;
- C1= 2.0;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0, 90]\,[deg]$, $\varphi \in [0, 90]\,[deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

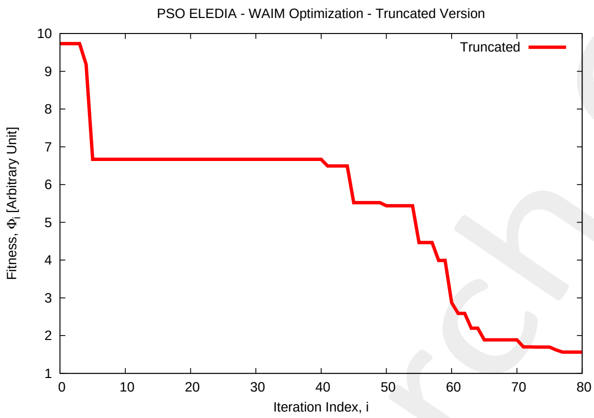
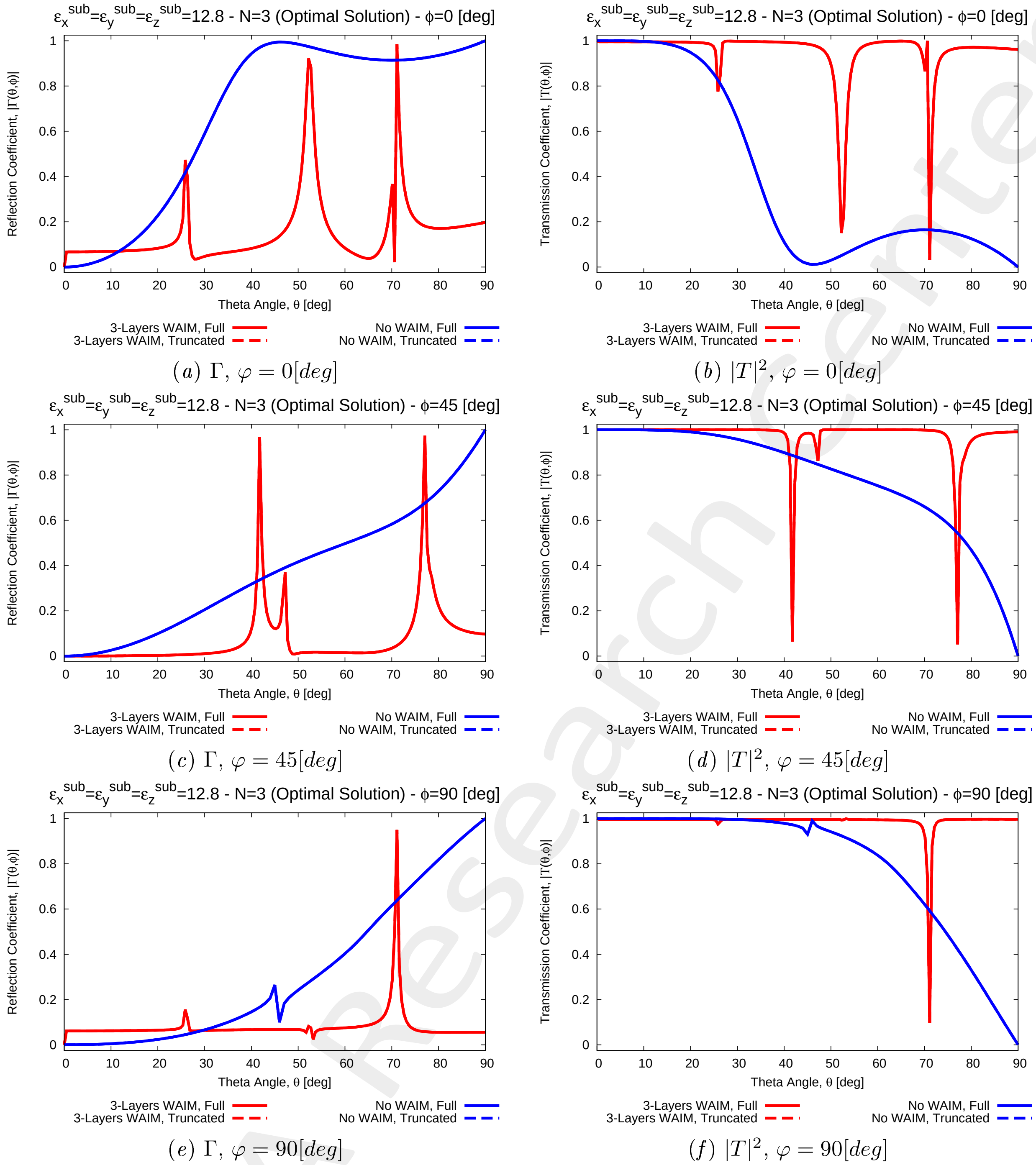


Figure 14: Fitness Dynamics.

$$Simulation\,time\,(Truncated):\;419m\,36s$$

Tool	*Optimal Solution*												*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\ [\lambda]$	ε_x^3	ε_y^3	ε_z^3	$h^3\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	18.19	11.23	21.70	0.034	34.83	6.26	24.28	0.033	1.63	20.90	14.54	0.43	9.733	1.563

Table 7: Optimal Solution.

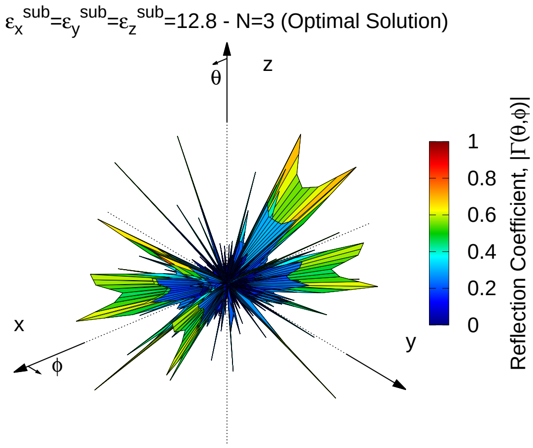


(a) Γ, $\varphi = 0[deg]$ (b) $|T|^2$, $\varphi = 0[deg]$

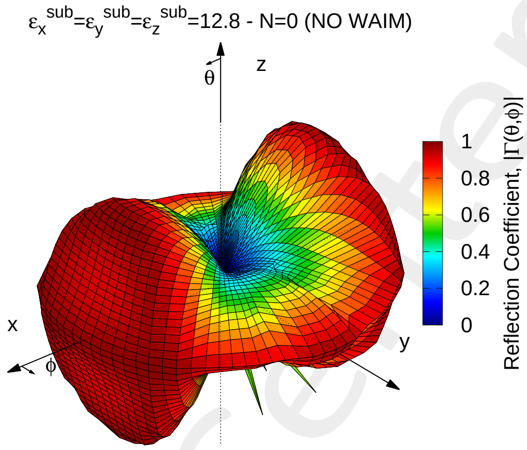
(c) Γ, $\varphi = 45[deg]$ (d) $|T|^2$, $\varphi = 45[deg]$

(e) Γ, $\varphi = 90[deg]$ (f) $|T|^2$, $\varphi = 90[deg]$

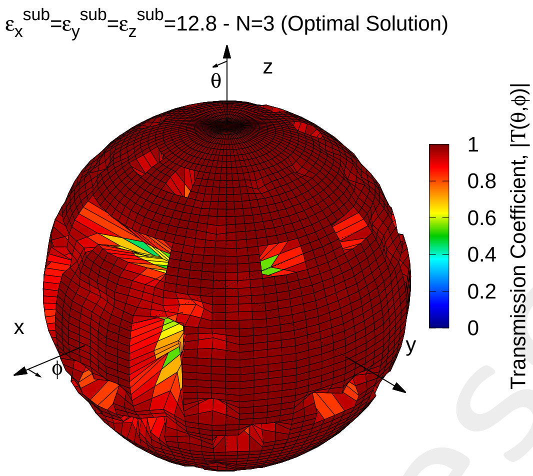
Figure 15: Reflection Coefficient along φ cuts, 3 Layers WAIM.



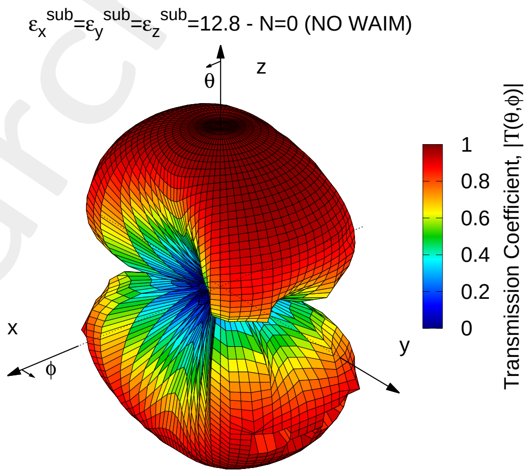
(a) Γ, 3 Layers WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 2 Layers WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 16: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	663.46	149.57	−77.46%
Truncated	663.51	149.44	−77.48%

Table 8: Cost Function Improvement.

1.1.5 Test Case #11 - Single Frequency - 3 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = \varepsilon^3 = [1 : 35] + j0$ - Triangular Lattice - $\varepsilon^{sub} = 12.8$ Tests

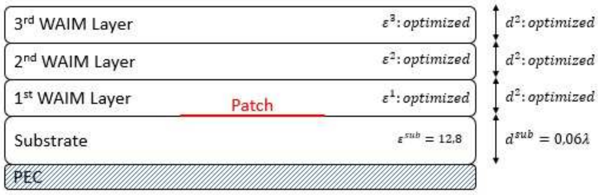


Figure 17: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.15$, $l = 0.098$ $[\lambda]$;
- Probe position: $x = 0.049$, $y = 0.0$ $[\lambda]$;
- Substrate: $\varepsilon_x = 12.8 + j0$, $\varepsilon_y = 12.8 + j0$, $\varepsilon_z = 12.8 + j0$, $d = 0.06[\lambda]$
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.0, 0.5)$, $s_2 = (0.433, 0.25)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 3$;
- Unknowns: $U = 12$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight= 0.4;
- Alpha= 0.4;
- Beta= 0.4;
- C1= 2.0;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

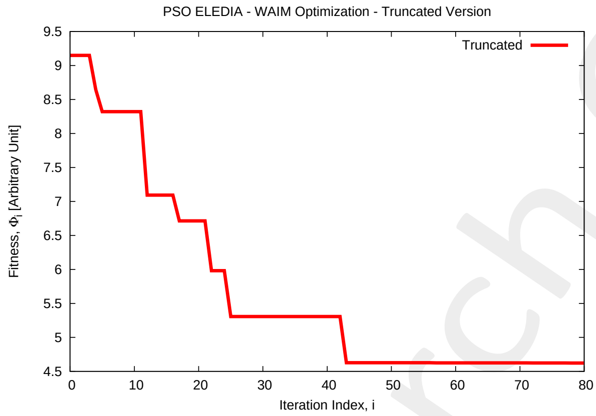
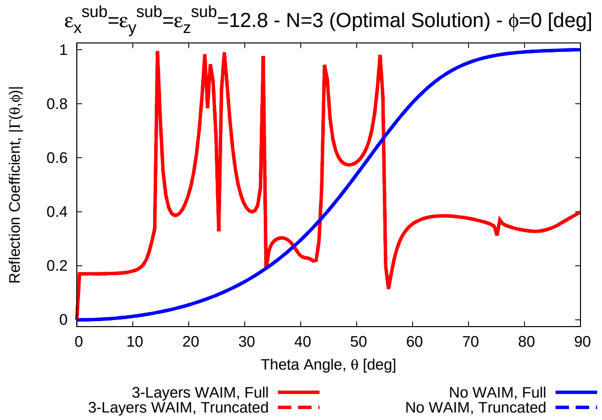


Figure 18: Fitness Dynamics.

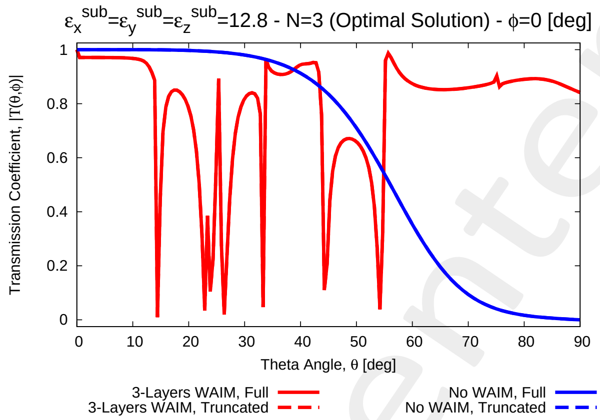
$$Simulation\, time\, (Truncated): 440m\, 5s$$

Tool	*Optimal Solution*												*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\ [\lambda]$	ε_x^3	ε_y^3	ε_z^3	$h^3\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	12.74	1.36	34.97	0.50	20.29	8.88	1.00	0.49	34.99	2.50	1.98	0.033	9.149	4.622

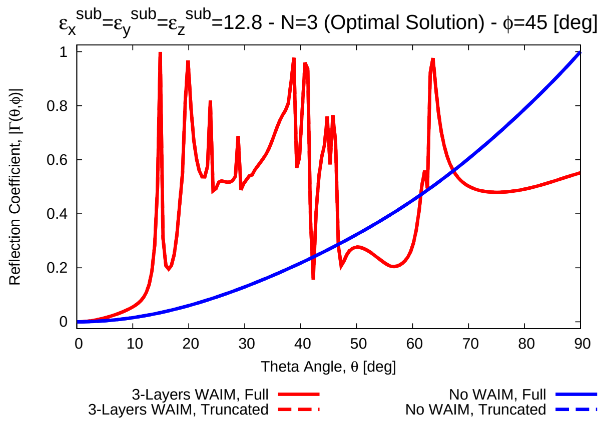
Table 9: Optimal Solution.



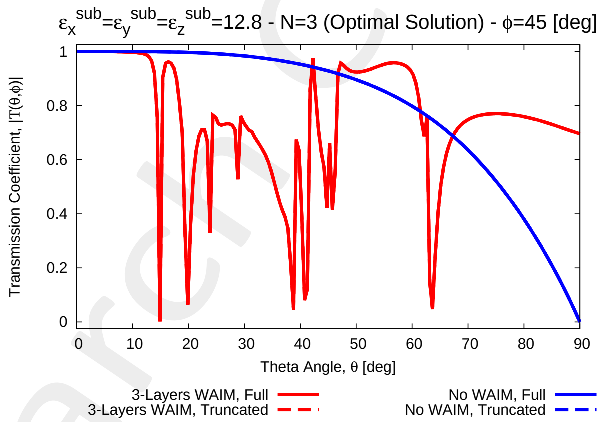
$(a)\ \Gamma,\ \varphi = 0[deg]$



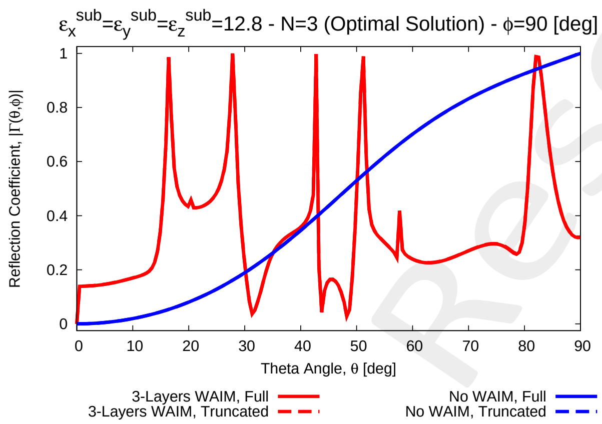
$(b)\ |T|^2,\ \varphi = 0[deg]$



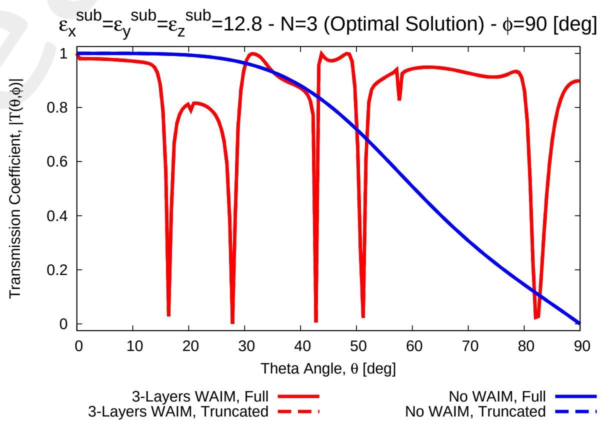
$(c)\ \Gamma,\ \varphi = 45[deg]$



$(d)\ |T|^2,\ \varphi = 45[deg]$

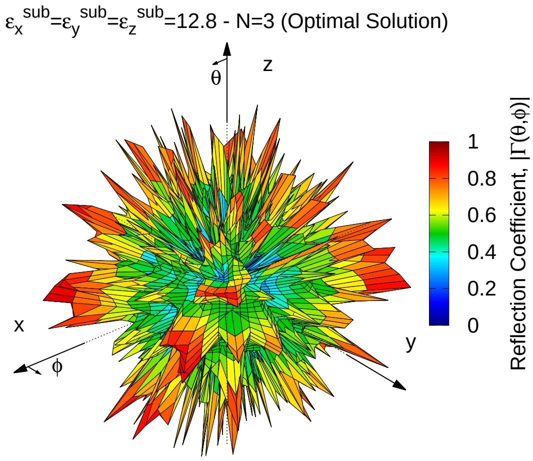


$(e)\ \Gamma,\ \varphi = 90[deg]$

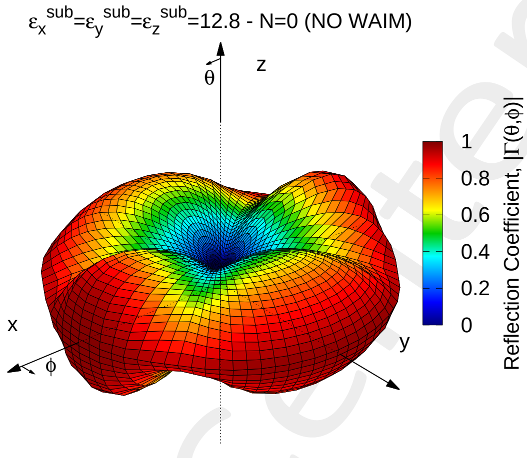


$(f)\ |T|^2,\ \varphi = 90[deg]$

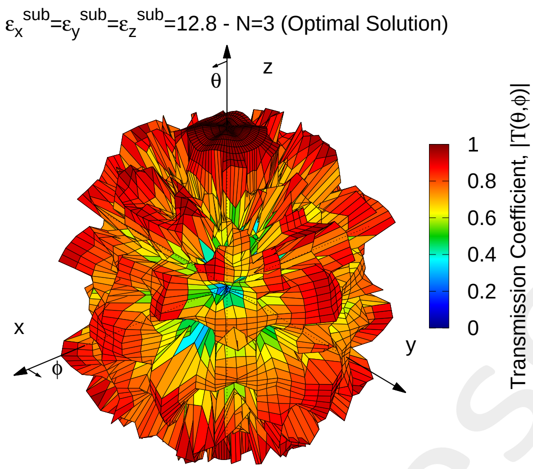
Figure 19: Reflection Coefficient along φ cuts, 3 Layers WAIM.



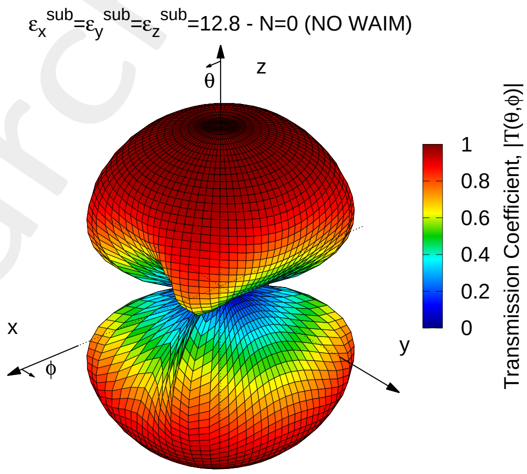
(a) Γ, 3 Layers WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 3 Layers WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 20: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	605.72	643.09	6.17%
Truncated	605.64	643.37	6.23%

Table 10: Cost Function Improvement.

1.2 $\varepsilon^{sub} = 2.2$ Tests

1.2.1 Test Case #3 - Single Frequency - 1 Anisotropic WAIM Layer - $\varepsilon^1 = [1 : 35]+j0$ - Triangular Lattice - $\varepsilon^{sub} = 2.2$ Tests

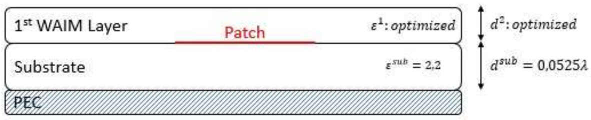


Figure 21: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.395$, $l = 0.302$ $[\lambda]$;
- Probe position: $x = 0.0766$, $y = 0.1975$ $[\lambda]$;
- Substrate: $\varepsilon_x = 2.2 + j0$, $\varepsilon_y = 2.2 + j0$, $\varepsilon_z = 2.2 + j0$, $d = 0.0525[\lambda]$
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.0, 0.5)$, $s_2 = (0.433, 0.25)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 1$;
- Unknowns: $U = 4$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight$= 0.4$;
- Alpha$= 0.4$;
- Beta$= 0.4$;
- C1$= 2.0$;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

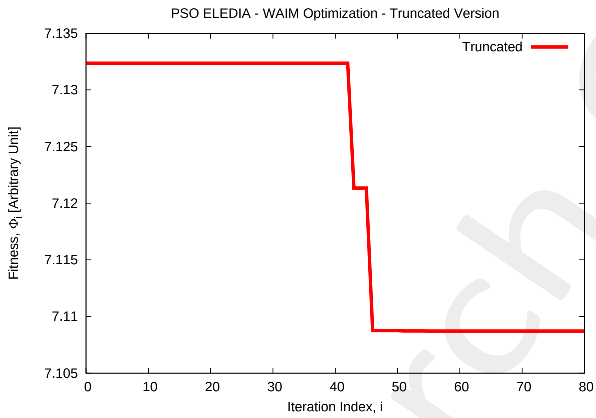
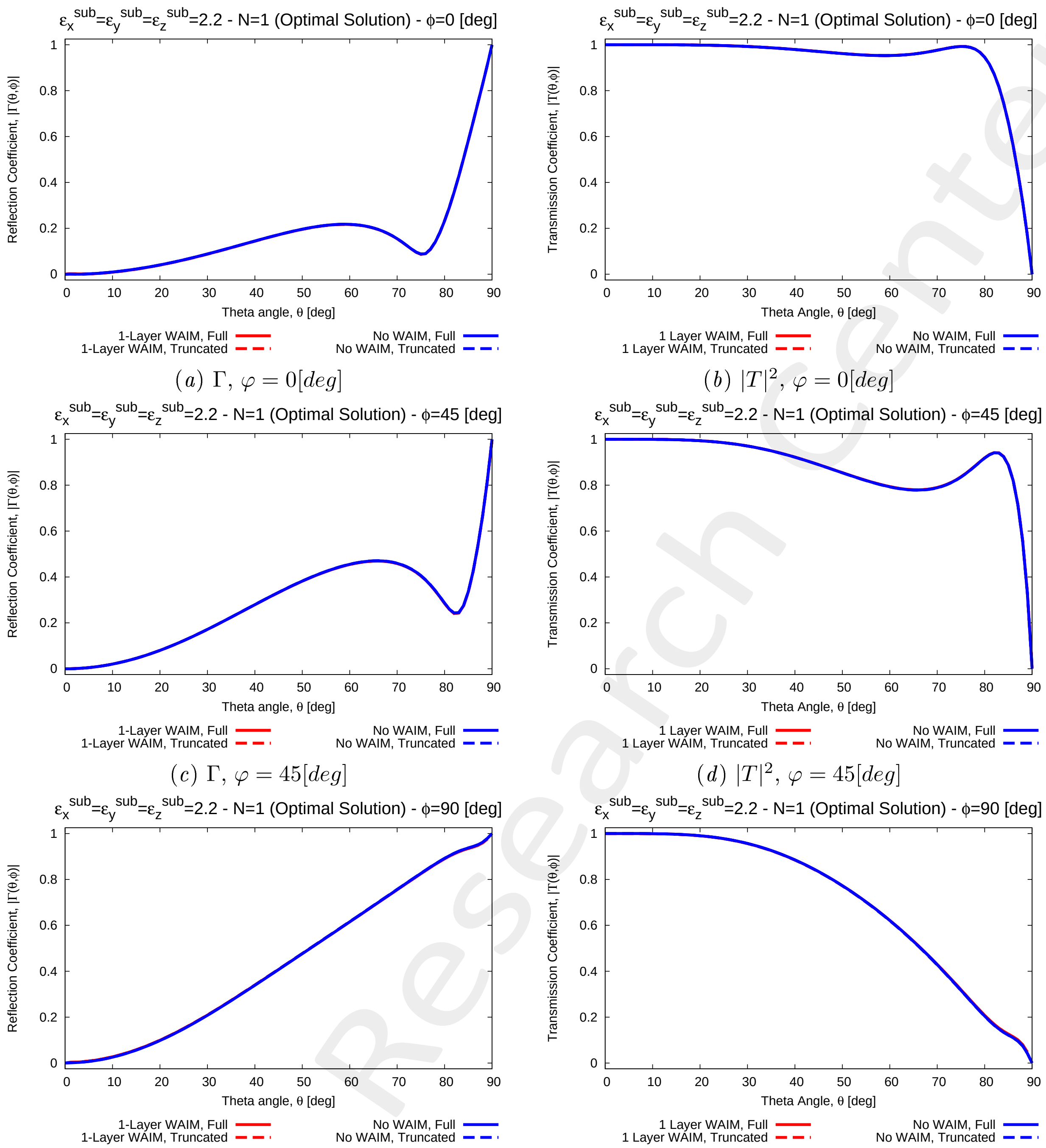


Figure 22: Fitness Dynamics.

$$Simulation\,time\,(Truncated):\ 374m\,11s$$

Tool	*Optimal Solution*				*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	1.00	1.04	17.85	0.033	7.132	7.109

Table 11: Optimal Solution.



(a) Γ, $\varphi = 0[deg]$

(b) $|T|^2$, $\varphi = 0[deg]$

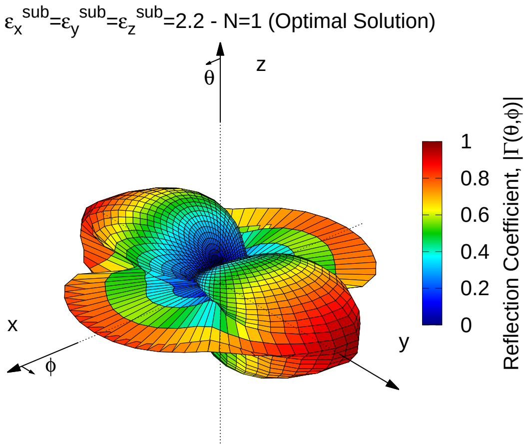
(c) Γ, $\varphi = 45[deg]$

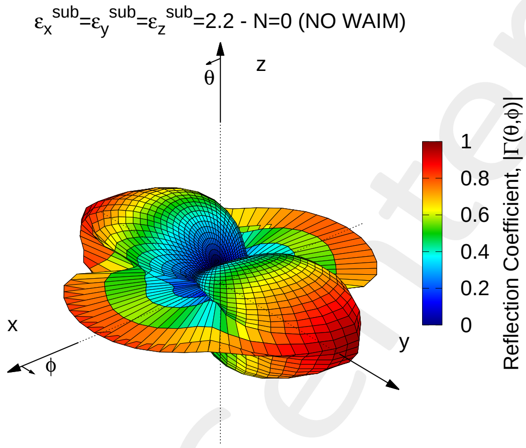
(d) $|T|^2$, $\varphi = 45[deg]$

(e) Γ, $\varphi = 90[deg]$

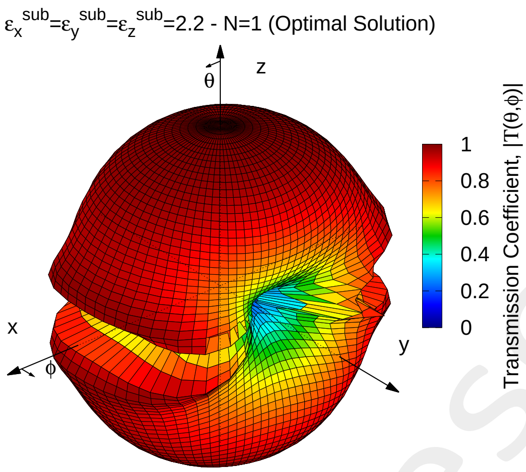
(f) $|T|^2$, $\varphi = 90[deg]$

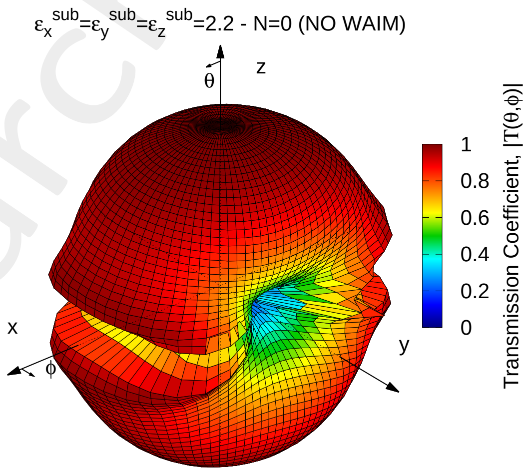
Figure 23: Reflection Coefficient along φ cuts, 1 Layer WAIM.





(a) Γ, 1 Layer WAIM, "Full" (b) Γ, No-WAIM





(c) $|T|^2$, 1 Layer WAIM, "Full" (d) $|T|^2$, No-WAIM

Figure 24: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	428.16	427.99	-0.04%
Truncated	428.57	428.20	-0.09%

Table 12: Cost Function Improvement.

1.2.2 Test Case #5 - Single Frequency - 2 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = [1 : 35] + j0$ - Square Lattice - $\varepsilon^{sub} = 2.2$ Tests

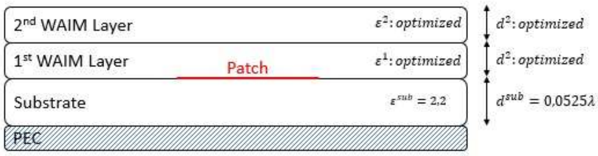


Figure 25: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.395$, $l = 0.302$ $[\lambda]$;
- Probe position: $x = 0.0766$, $y = 0.1975$ $[\lambda]$;
- Substrate: $\varepsilon_x = 2.2 + j0$, $\varepsilon_y = 2.2 + j0$, $\varepsilon_z = 2.2 + j0$, $d = 0.0525[\lambda]$
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.5, 0.0)$, $s_2 = (0.0, 0.5)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 2$;
- Unknowns: $U = 8$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight$= 0.4$;
- Alpha$= 0.4$;
- Beta$= 0.4$;
- C1$= 2.0$;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

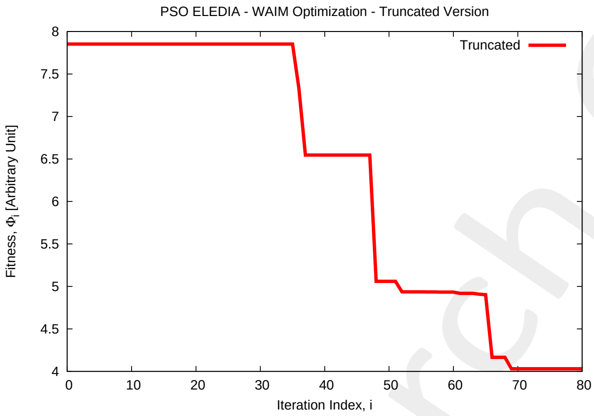
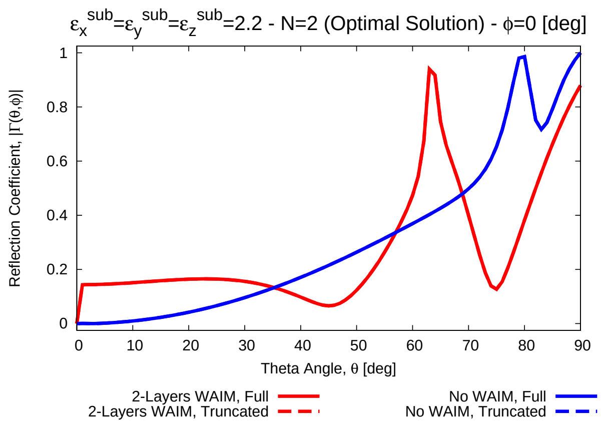


Figure 26: Fitness Dynamics.

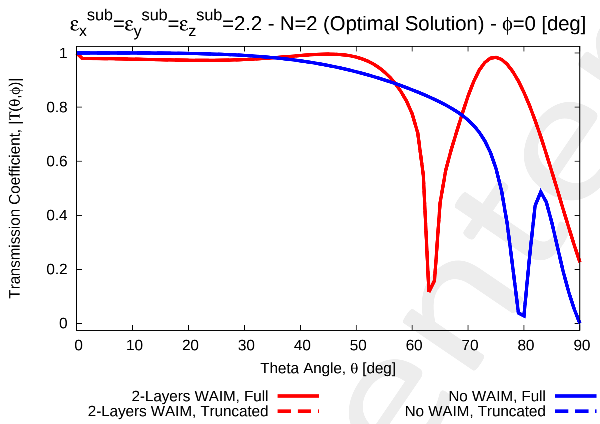
$$Simulation\,time\,(Truncated):\ 400m\,38s$$

$Tool$	$Optimal\,Solution$								$Fitness\,Value$	
	ε_x^1	ε_y^1	ε_z^1	$h^1\,[\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\,[\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
$Truncated$	1.04	34.84	6.61	0.18	3.34	13.49	26.77	0.10	7.853	4.031

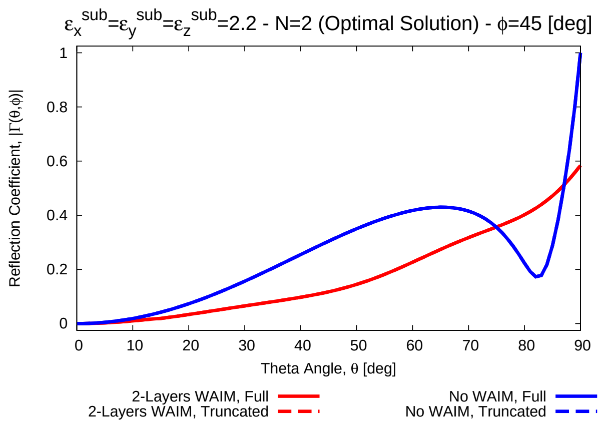
Table 13: Optimal Solution.



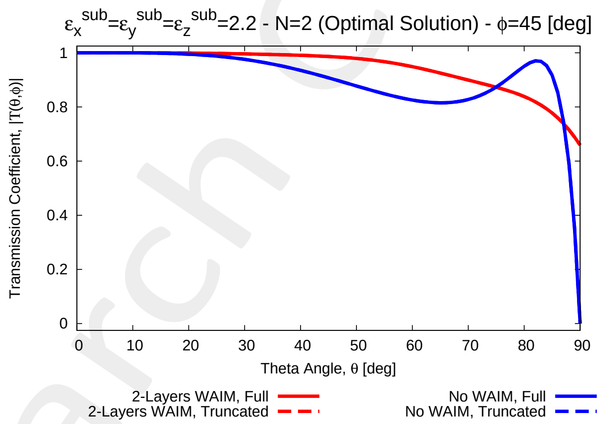
(a) Γ, $\varphi = 0[deg]$



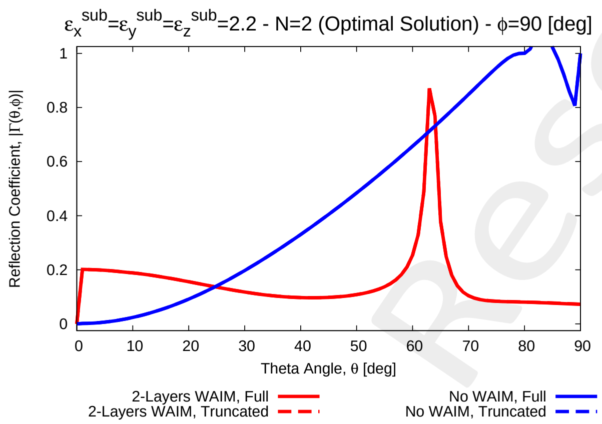
(b) $|T|^2$, $\varphi = 0[deg]$



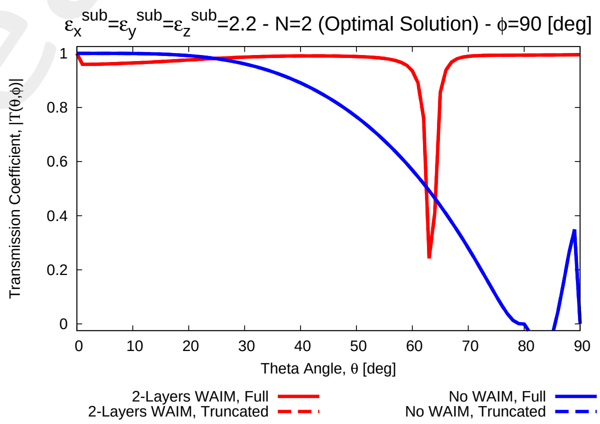
(c) Γ, $\varphi = 45[deg]$



(d) $|T|^2$, $\varphi = 45[deg]$

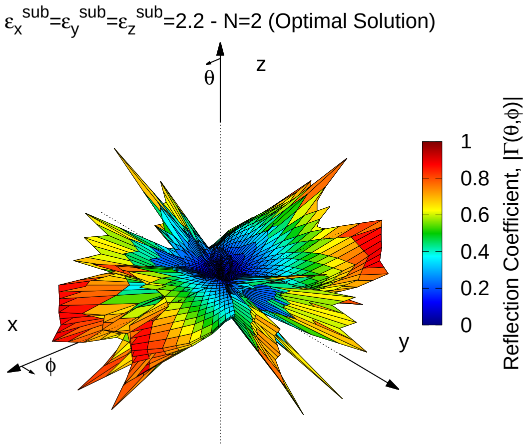


(e) Γ, $\varphi = 90[deg]$

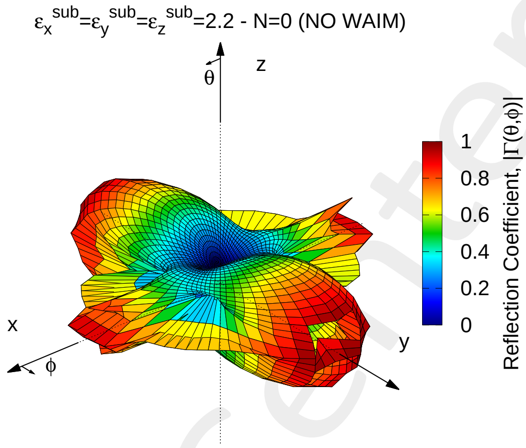


(f) $|T|^2$, $\varphi = 90[deg]$

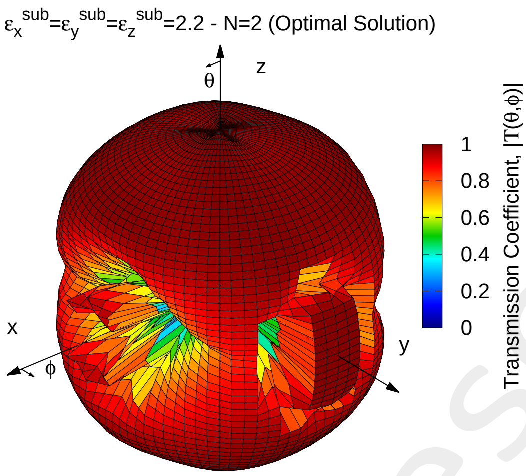
Figure 27: Reflection Coefficient along φ cuts, 2 Layers WAIM.



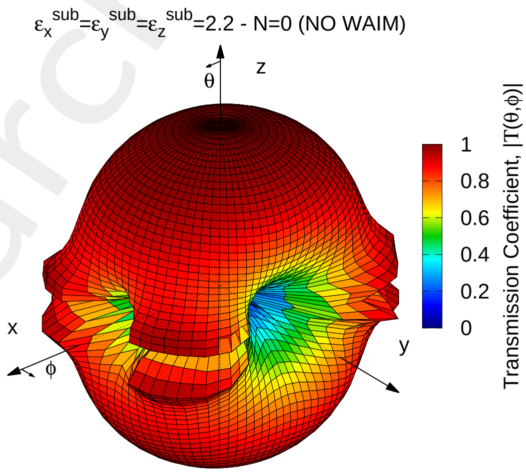
(a) Γ, 2 Layers WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 2 Layers WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 28: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	452.51	322.57	-28.71%
Truncated	452.59	322.66	-28.71%

Table 14: Cost Function Improvement.

1.2.3 Test Case #7 - Single Frequency - 2 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = [1 : 35] + j0$ - Triangular Lattice - $\varepsilon^{sub} = 2.2$ Tests

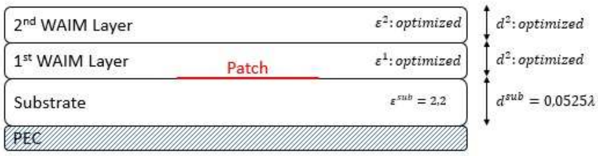


Figure 29: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.395$, $l = 0.302$ $[\lambda]$;
- Probe position: $x = 0.0766$, $y = 0.1975$ $[\lambda]$;
- Substrate: $\varepsilon_x = 2.2 + j0$, $\varepsilon_y = 2.2 + j0$, $\varepsilon_z = 2.2 + j0$, $d = 0.0525[\lambda]$
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.0, 0.5)$, $s_2 = (0.433, 0.25)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 2$;
- Unknowns: $U = 8$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight$= 0.4$;
- Alpha$= 0.4$;
- Beta$= 0.4$;
- C1$= 2.0$;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

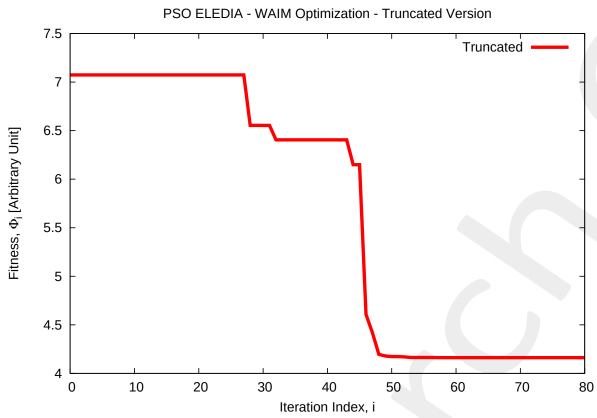


Figure 30: Fitness Dynamics.

$$Simulation\,time\,(Truncated):\ 452m\,49s$$

Tool	*Optimal Solution*								*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	1.02	1.07	17.38	0.19	2.89	29.44	1.74	0.40	7.074	4.162

Table 15: Optimal Solution.

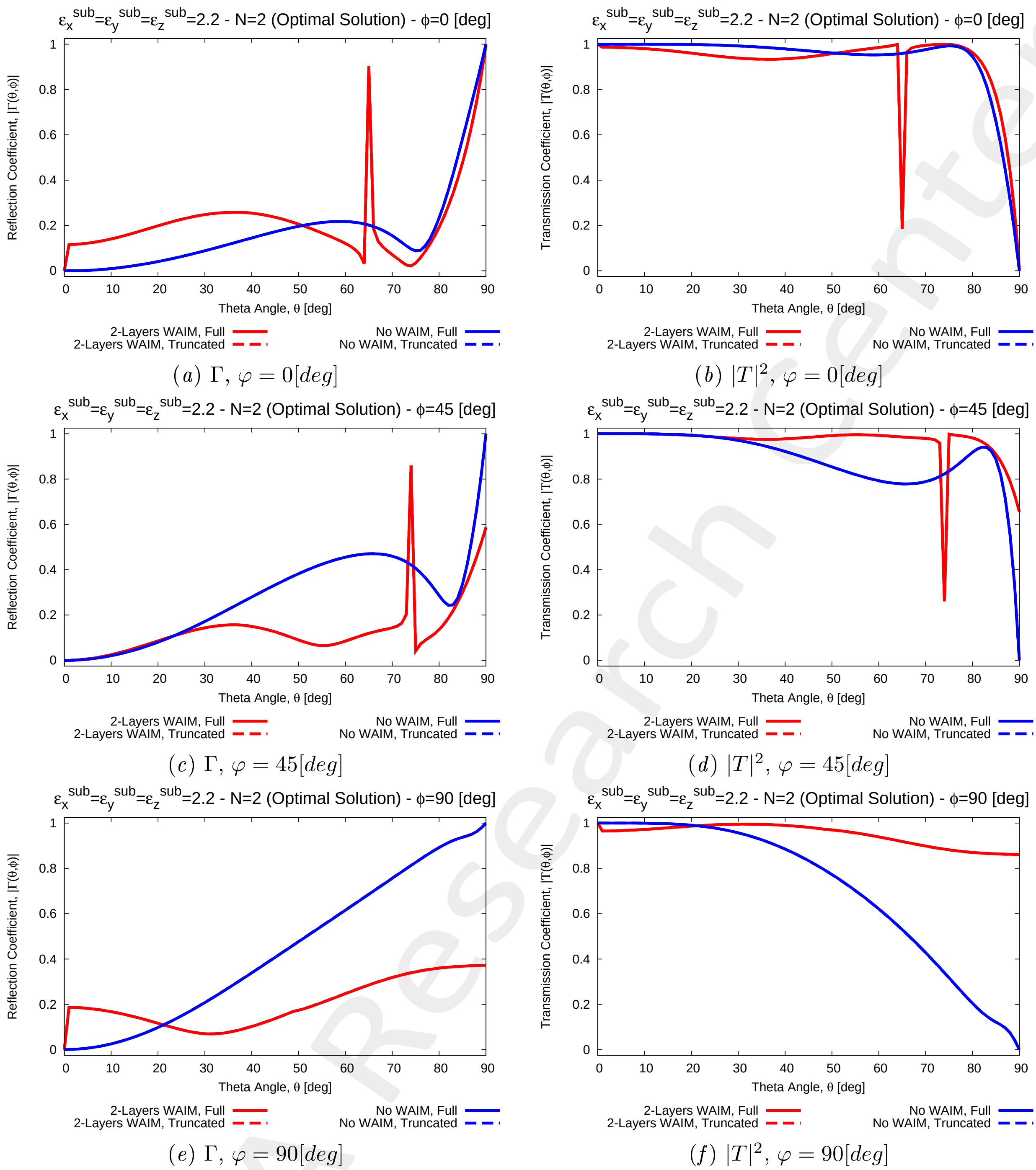
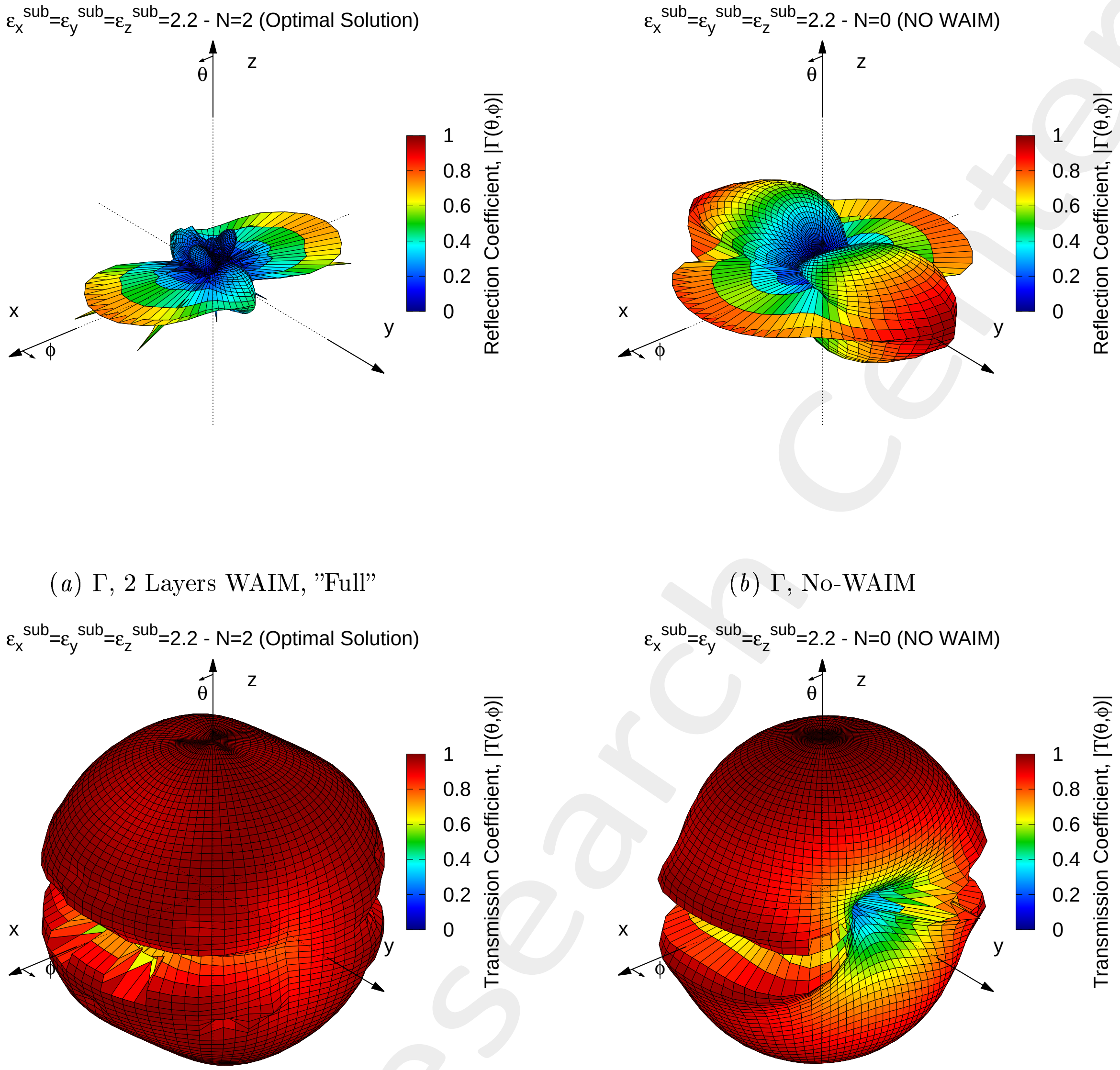


Figure 31: Reflection Coefficient along φ cuts, 2 Layers WAIM.



(*a*) Γ, 2 Layers WAIM, "Full"

(*b*) Γ, No-WAIM

(*c*) $|T|^2$, 2 Layers WAIM, "Full"

(*d*) $|T|^2$, No-WAIM

Figure 32: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	428.16	257.95	-39.75%
Truncated	428.57	258.15	-39.76%

Table 16: Cost Function Improvement.

1.2.4 Test Case #9 - Single Frequency - 3 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = \varepsilon^3 = [1\,:\,35] + j0$ - Square Lattice - $\varepsilon^{sub} = 2.2$ Tests

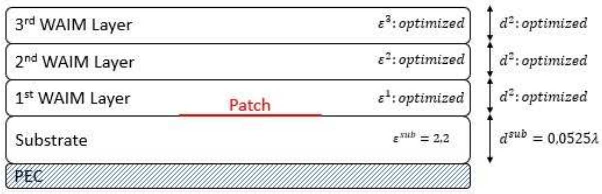


Figure 33: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.395$, $l = 0.302$ $[\lambda]$;
- Probe position: $x = 0.0766$, $y = 0.1975$ $[\lambda]$;
- Substrate: $\varepsilon_x = 2.2 + j0$, $\varepsilon_y = 2.2 + j0$, $\varepsilon_z = 2.2 + j0$, $d = 0.0525[\lambda]$
- Floquet coefficient = 121;
- Lattice basis: $s_1 = (0.5, 0.0)$, $s_2 = (0.0, 0.5)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 3$;
- Unknowns: $U = 12$;
- Unknown ranges: $\varepsilon_x = [1\,:\,35] + j0$, $\varepsilon_y = [1\,:\,35] + j0$, $\varepsilon_z = [1\,:\,35] + j0$, $d = [0.033\,:\,0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight= 0.4;
- Alpha= 0.4;
- Beta= 0.4;
- C1= 2.0;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

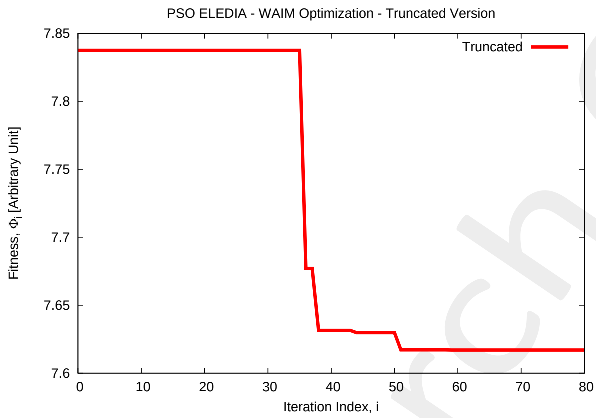
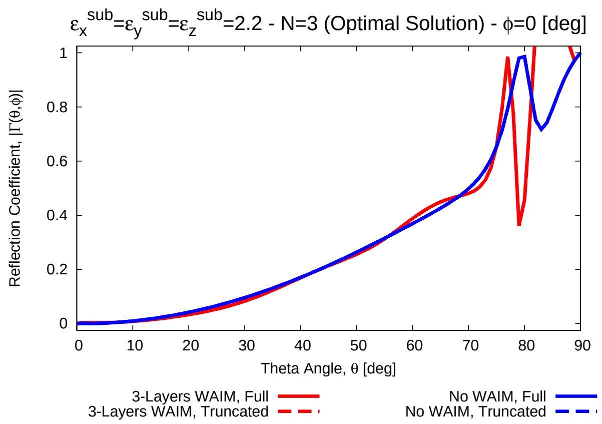


Figure 34: Fitness Dynamics.

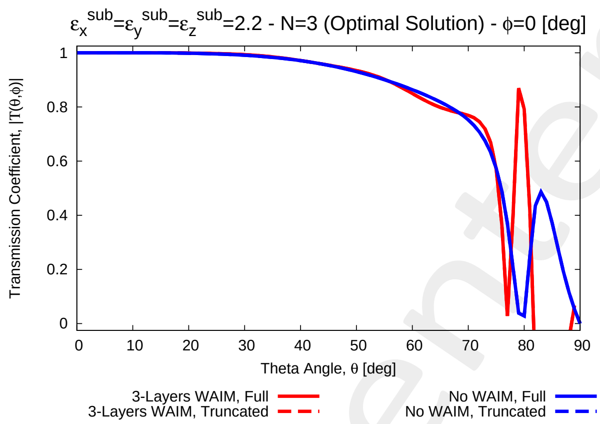
$$Simulation\,time\,(Truncated):\ 419m\,24s$$

Tool	*Optimal Solution*												*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	h^1 $[\lambda]$	ε_x^2	ε_y^2	ε_z^2	h^2 $[\lambda]$	ε_x^3	ε_y^3	ε_z^3	h^3 $[\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	1.00	1.00	1.00	0.50	1.04	1.00	1.01	0.43	1.07	1.05	1.00	0.50	7.837	7.617

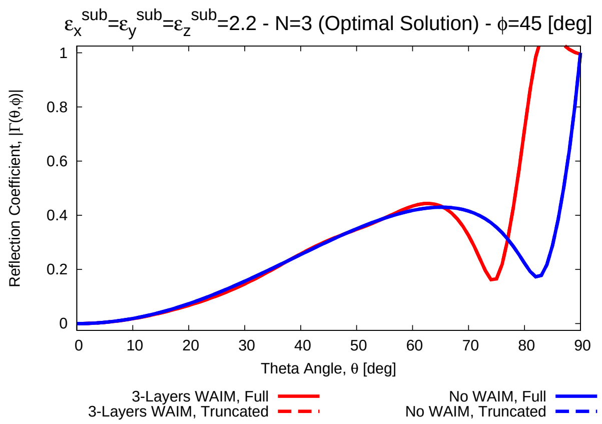
Table 17: Optimal Solution.



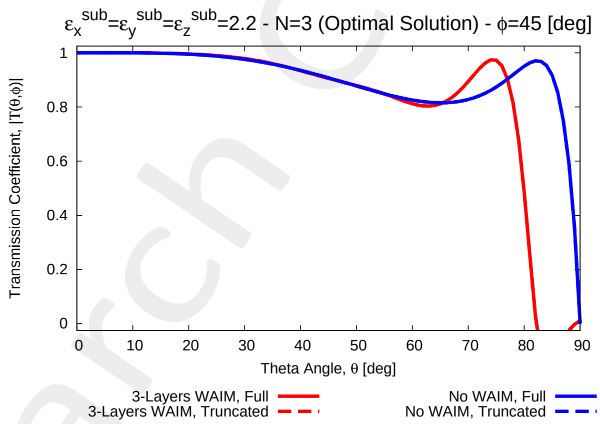
$(a)\ \Gamma,\ \varphi = 0[deg]$



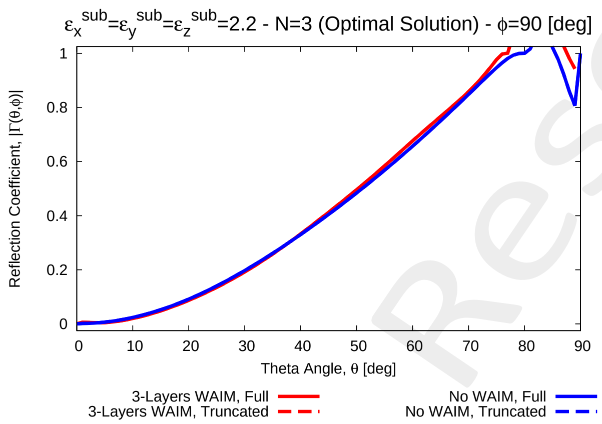
$(b)\ |T|^2,\ \varphi = 0[deg]$



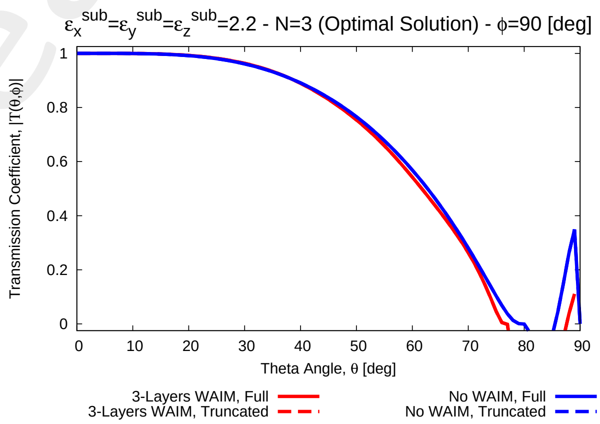
$(c)\ \Gamma,\ \varphi = 45[deg]$



$(d)\ |T|^2,\ \varphi = 45[deg]$

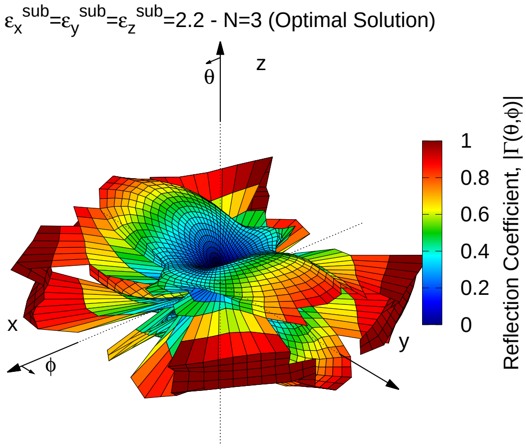


$(e)\ \Gamma,\ \varphi = 90[deg]$

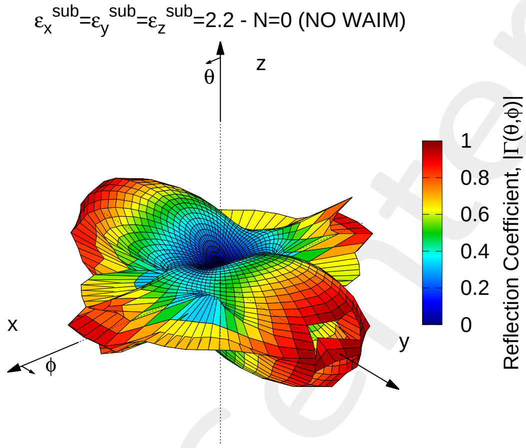


$(f)\ |T|^2,\ \varphi = 90[deg]$

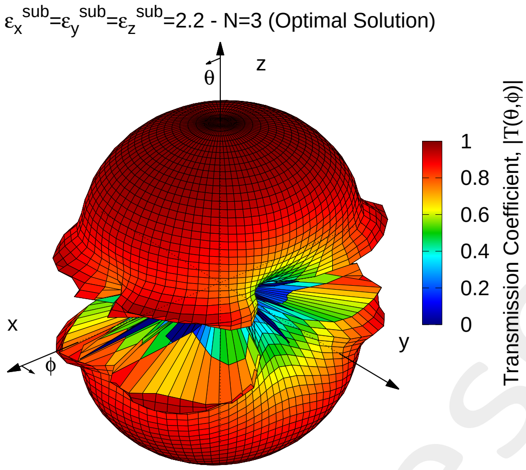
Figure 35: Reflection Coefficient along φ cuts, 3 Layers WAIM.



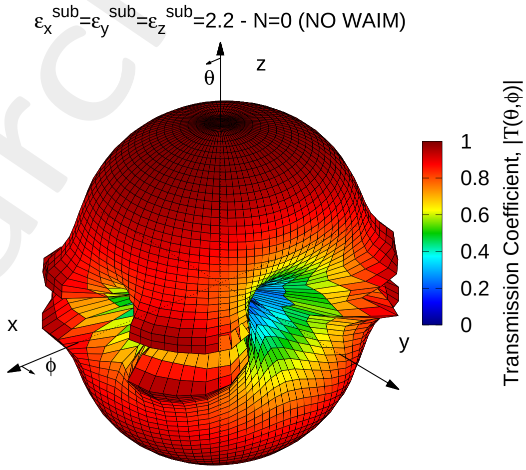
(a) Γ, 3 Layers WAIM, "Full"



(b) Γ, No-WAIM



(c) $|T|^2$, 3 Layers WAIM, "Full"



(d) $|T|^2$, No-WAIM

Figure 36: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	452.51	514.43	13.69%
Truncated	452.59	514.53	13.69%

Table 18: Cost Function Improvement.

1.2.5 Test Case #11 - Single Frequency - 3 Anisotropic WAIM Layers - $\varepsilon^1 = \varepsilon^2 = \varepsilon^3 = [1 : 35] + j0$ - Triangular Lattice - $\varepsilon^{sub} = 2.2$ Tests

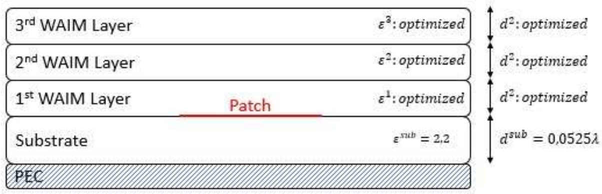


Figure 37: Test Case Schema.

Simulation Parameters:

- Frequency: $f = 10[GHz]$;
- Patch dimensions: $w = 0.395$, $l = 0.302$ $[\lambda]$;
- Probe position: $x = 0.0766$, $y = 0.1975$ $[\lambda]$;
- Substrate: $\varepsilon_x = 2.2 + j0$, $\varepsilon_y = 2.2 + j0$, $\varepsilon_z = 2.2 + j0$, $d = 0.0525[\lambda]$
- Floquet coefficient $= 121$;
- Lattice basis: $s_1 = (0.0, 0.5)$, $s_2 = (0.433, 0.25)$ $[\lambda]$;

Analysis Parameters:

- Samples analysis (phi cuts): $\theta \in [0, 90]$ $[deg]$, $\varphi \in [0, 90]$ $[deg]$, $\theta_{samples} = 91$, $\varphi_{samples} = 3$;
- Samples analysis (3D plots): $\theta \in [-180, 180]$ $[deg]$, $\varphi \in [-90, 90]$ $[deg]$, $\theta_{samples} = 72$, $\varphi_{samples} = 21$;

PSO Synthesis Parameters:

- Number of WAIM Layers: $N = 3$;
- Unknowns: $U = 12$;
- Unknown ranges: $\varepsilon_x = [1 : 35] + j0$, $\varepsilon_y = [1 : 35] + j0$, $\varepsilon_z = [1 : 35] + j0$, $d = [0.033 : 0.5]$ $[\lambda]$;
- Swarm size: $P = 6$;
- Max iteration number: $I = 80$;
- Inertial weight= 0.4;
- Alpha= 0.4;
- Beta= 0.4;
- C1= 2.0;

- C2= 2.0;
- Random seed= 26;
- No-WAIM case implemented by the first particle at the 1^{st} iteration;
- Samples synthesis (phi cuts): $\theta \in [0,\ 90]\ [deg]$, $\varphi \in [0,\ 90]\ [deg]$, $\theta_{samples} = 7$, $\varphi_{samples} = 3$;

Optimization Results

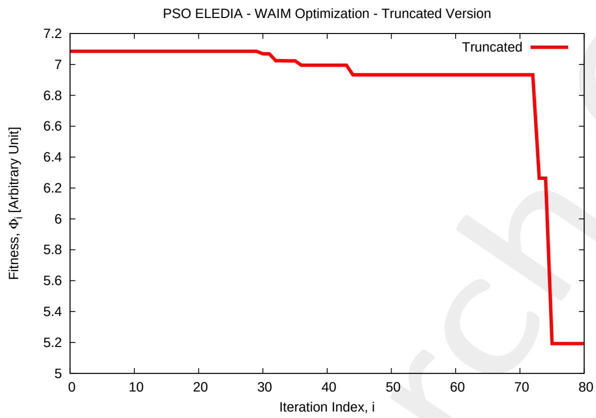


Figure 38: Fitness Dynamics.

$$Simulation\,time\,(Truncated):\ 442m\,18s$$

Tool	*Optimal Solution*												*Fitness Value*	
	ε_x^1	ε_y^1	ε_z^1	$h^1\ [\lambda]$	ε_x^2	ε_y^2	ε_z^2	$h^2\ [\lambda]$	ε_x^3	ε_y^3	ε_z^3	$h^3\ [\lambda]$	$\Phi_{i=0}$	$\Phi_{I=80}$
Truncated	1.41	1.04	1.00	0.15	11.89	1.05	2.45	0.042	2.77	5.20	1.00	0.49	7.085	5.193

Table 19: Optimal Solution.

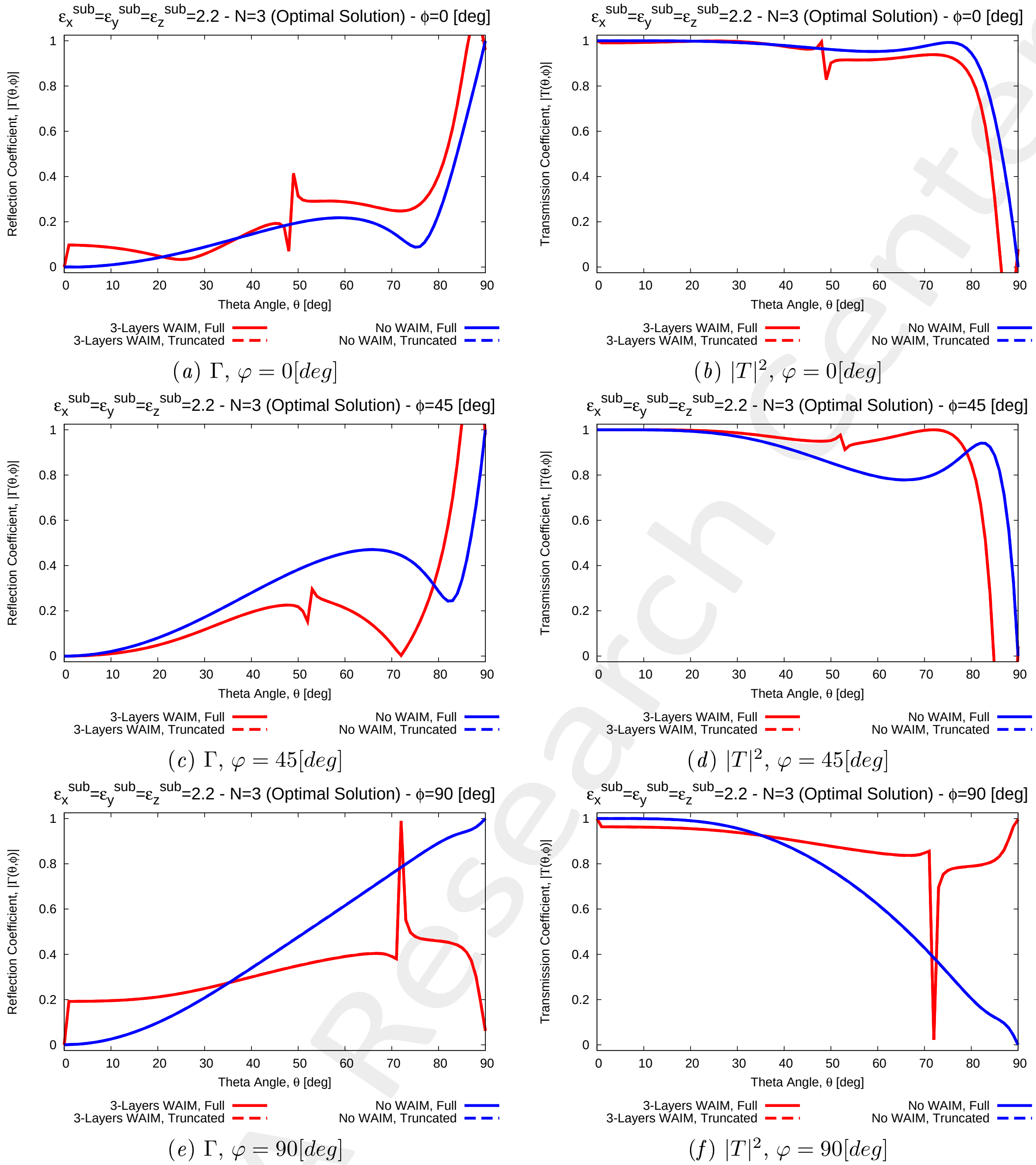
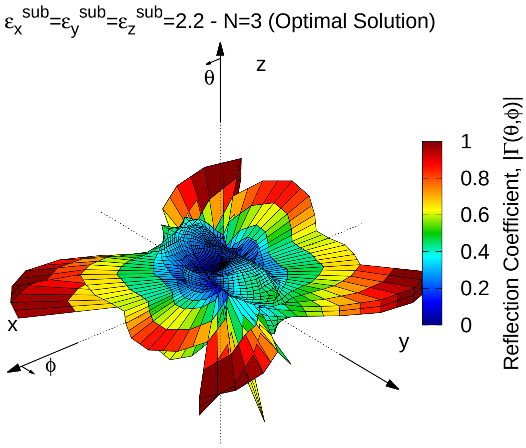
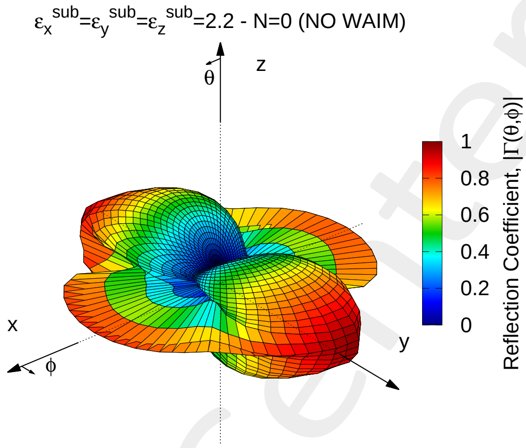


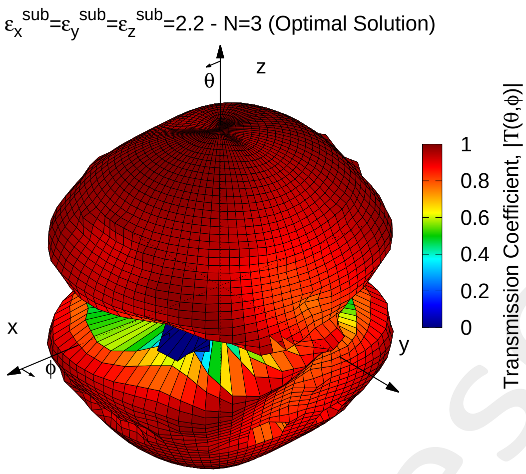
Figure 39: Reflection Coefficient along φ cuts, 3 Layers WAIM.



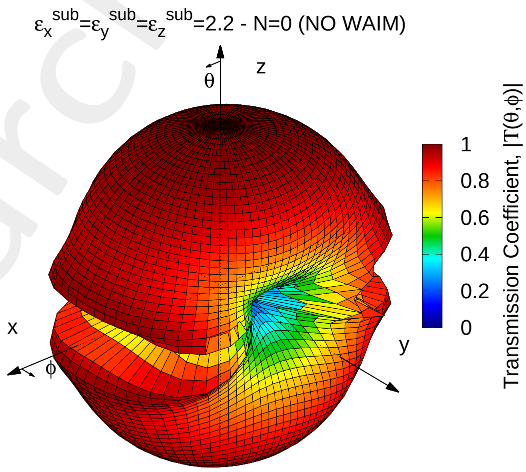
(*a*) Γ, 3 Layers WAIM, ”Full”



(*b*) Γ, No-WAIM



(*c*) $|T|^2$, 3 Layers WAIM, ”Full”



(*d*) $|T|^2$, No-WAIM

Figure 40: Reflection Coefficient and Transmission Coefficient

Tool	*Cost Function*		*Improvement Percentage*
	Φ_0^{fine}	Φ_{SbD}^{fine}	
Full	428.16	385.10	-10.06%
Truncated	428.57	385.41	-10.07%

Table 20: Cost Function Improvement.

More information on the topics of this document can be found in the following list of references.

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