Enhancing the Performance of Photonic Crystal AND Gates with Machine Learning Optimization

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***Abstract*— Recent advances in photonic crystals have opened up new possibilities for developing high-speed, low-power optical devices. One promising application is using photonic crystals to realize AND gates, fundamental building blocks in digital logic circuitry. This paper presents a machine learning-based approach to optimizing the performance of AND gates. We utilize the Extra Trees Regressor model to train on a dataset of simulation results and predict the output power for different input and parameter configurations. Our results show that the model can accurately predict the output power with an RMSE (Root Mean Square Error) of 0.18. We then use the model to identify optimal parameter settings for the radius of the rods and the lattice constant. We find that the optimal parameters are R=0.05 um and x=0.12 um. The paper further scrutinizes the optimization process for optical gate outputs, leveraging predictions from the Extra Trees Regressor for conditional calculations. It meticulously examines the impact of parameters such as rod radius and lattice constant on gate functionality, emphasizing their role in achieving desired output states. Simulation results elucidate the efficacy of optimized parameters in realizing the behavior of an AND gate within the photonic crystal framework.**

Keywords*— *Optical AND gate, photonic crystal, Extra Trees Regressor, Optimization Techniques

I. Introduction

The transmission of information via electronic circuits can be significantly enhanced by integrating multiple circuits and minimizing their size. However, as the number of circuits decreases considerably over time, downsizing encounters substantial challenges. Consequently, researchers are compelled to seek fundamental solutions to enhance the speed of electrical devices [1–8].

One of the areas capturing researchers' attention is the exploration of periodic structures at micrometer scales, often referred to as photonic crystals. These structures consist of two materials arranged alternately, each with distinct refractive indices, resulting in a periodic structure. If this periodicity exists in only one direction, it is termed a one-dimensional photonic crystal. Similarly, it is called a two-dimensional photonic crystal if present in two directions, and a three-dimensional photonic crystal if found in three directions [9–17]. The fundamental concept underlying photonic band gap (PBG) crystals is the creation of a spectrum of continuous wavelengths that, due to the characteristics of PBG, cannot pass through the structure. Consequently, these wavelengths get reflected upon encountering the structure. This characteristic enables the guidance of light within photonic crystals, serving as waveguides along predetermined pathways [18–25].

One of the noteworthy applications of photonic crystals in electronics is the development of logical gates and circuits. These circuits utilize light sources as inputs, with logic 0 and 1 determined based on the detected optical power. Here, high power denotes logic 1, while low power represents logic 0. The creation of a logical gate or circuit involves trial and error, adjusting chosen physical parameters until achieving desirable and robust values of 0 and 1 [26–47].

In some previous research, the focus was on applying machine learning techniques, particularly utilizing data primarily derived from various simulations. To achieve optimal outputs, The K-Nearest Neighbors (KNN) regression technique was employed [48]. Presently, we aim to optimize the AND gate. This revised version aims to refine and clarify the discussion on integrating photonic crystals in electronic circuits and applying machine learning techniques, focusing on optimizing logical gates.

II. AND logic gate

Fig .1 shows the proposed structure for the AND gate. In this structure, two inputs, X and Y, are used. The lattice constant is a=0.6µm, and the radius of the rods R=0.12µm are selected. The rods are made of silicon. Two waveguide paths are created by removing the rods on the left, with the X and Y light sources placed at their entrances. Removing some rods has also created a vertical path that connects the entrances. To achieve a better result, the central rod R0 is changed in the X direction to achieve the best output state. In other words, we want to know how much the rod R0 should be moved in the x direction to get better outputs.

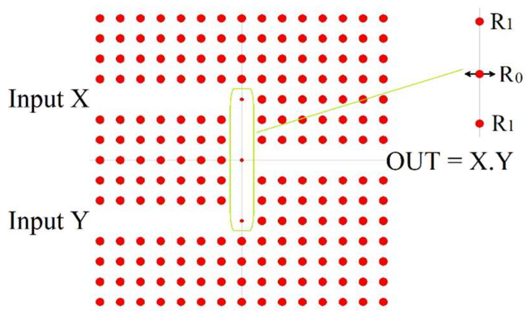

Fig. 1. Proposed basic structure for an all-optical AND logic gate

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III. MACHINE LEARNING: ENHANCING PHOTONIC CRYSTAL AND GATES USING EXTRA TREES REGRESSOR

Currently, Artificial Intelligence (AI) permeates diverse industrial sectors, playing a pivotal role in propelling novel technologies forward. Within the AI spectrum, Machine Learning emerges as a prominent facet, enabling systems to learn autonomously sans explicit programming. Specifically, Machine Learning endeavors to cultivate intelligent systems capable of assimilating insights from data and experiences, augmenting their cognitive capabilities. The Machine Learning journey commences with data input, fostering the machine's adeptness in recognizing patterns within datasets, subsequently facilitating informed decision-making based on these discerned patterns and insights. At its core, Machine Learning seeks to endow machines with autonomous learning capacities, negating the need for human intervention while enabling adaptive adjustments in their operations. Within the realm of Machine Learning, a multitude of algorithms comes into play, identifying patterns and training systems through iterative processes utilizing expansive datasets. Diverging from traditional models reliant on predetermined equations, Machine Learning algorithms leverage computational and statistical methodologies to directly glean knowledge from data. Notably, the potency of these algorithms burgeons in tandem with the quantity of data assimilated during the learning phase [48]. This article specifically delves into the design intricacies of an AND gate utilizing photonic crystals, meticulously tailoring inputs and outputs to realize the desired gate configuration through meticulously selected waveguide paths. Subsequent phases involve simulations, exploring diverse physical parameters. Notably, the Extra Trees Regressor, an esteemed Machine Learning algorithm, takes center stage. This algorithm assists in determining optimal structure parameters, thereby shaping the definitive configuration for the AND gate.

IV. UTILIZING RMSE AND MAE FOR PRECISION ASSESSMENT

In our quest to identify the most accurate and precise algorithm for enhancing optical gate simulation software, we relied on two fundamental metrics: RMSE and MAE (Mean Absolute Error). These metrics serve as the bedrock of our assessment process, enabling us to pinpoint the model that offers the highest level of precision.

A. RMSE

The RMSE is mathematically expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}} \quad (1)$$

Where:

- n represents the number of data points.
- Y_i signifies the actual values.
- $\hat{Y}_i$ represents the predicted values.

A lower RMSE value indicates a higher degree of accuracy and precision. In our experiments, we sought a model with the lowest RMSE, signifying superior precision in predicting optical gate simulation outcomes.

B. MAE

The MAE is mathematically expressed as:

$$MAE = \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n} \quad (2)$$

Where:

- n represents the number of data points.
- Y_i signifies the actual values.
- $\hat{Y}_i$ represents the predicted values.

In the pursuit of enhancing precision and accuracy within optical gate simulation software, our study delved into the meticulous evaluation of various regression models. The aim was to identify the most adept model through rigorous analysis utilizing RMSE and MAE as pivotal metrics for assessment.

RMSE, a measure indicating the square root of the average of squared differences between predicted and actual values, stands as a foundational metric for evaluating the degree of error within predictive models. In contrast, a lower MAE value signifies a heightened level of precision, as it measures the average absolute differences between predicted and actual values. The integration of both RMSE and MAE was instrumental in ensuring the chosen model not only minimized error magnitudes but also captured precise predictions, devoid of significant biases [49].

Through rigorous evaluation, the Extra Trees Regressor emerged as a standout performer, showcasing exceptional proficiency in both RMSE and MAE. Its excellence is underscored by an RMSE of 0.18 (refer to Table 2), while Table 1 highlights the consistent accuracy observed across diverse scenarios, where MAE values consistently range between 0.0053 and 0.0822. This remarkable consistency distinctly positions the Model as the ideal candidate for seamless integration into our optical gate simulation software.

- **R11 and R10**: These are prediction outputs from the Extra Trees Regressor model. R11 is for scenarios where input A doesn't equal input B, and R10 is for scenarios where input A equals input B. They're used within an AND gate structure to assess the gate's behavior and output power under different input conditions.
- **X11 and X10**: These parameters are associated with the lattice constant or rod radius (denoted as "X"). They provide predictions from the Extra Trees Regressor model for different parameter configurations, helping in the optimization process to achieve desired output states within the optical gate.

TABLE 1: PERFORMANCE METRICS COMPARISON OF REGRESSION MODELS FOR OPTICAL GATE SIMULATION

Metric	R11	R10	X11	X10
MAE	0.0822	0.0269	0.0158	0.0053
MSE	0.0135	0.0014	0.0003	0.0001

V. Performance Comparison of Regression Models

Table 2 presents our extensive evaluation aimed at identifying the optimal algorithm for improving optical gate simulation software. Through a comprehensive assessment of multiple regression models, we offer a comparative analysis based on key performance metrics:

Table 2: Performance Comparison of Regression Models for Optical Gate Simulation

Algorithm	RMSE
Extra Trees Regressor	0.18
Gaussian Process Regressor	0.69
Hist Gradient Boosting Regressor	0.69
Huber Regressor	0.7
K Neighbors Regressor	0.73
Kernel Ridge	0.82
Lars	0.87
Lars CV	1.46
Lasso	1.46
Lasso CV	1.51

We observe significant variations in RMSE. The RMSE represents the accuracy of predictions, where lower values indicate higher precision. The Time Taken denotes the efficiency of the models in completing computations swiftly. Among these models, the Extra Trees Regressor clearly emerges as the frontrunner with an RMSE of 0.18 and a Time Taken of 0.38. It excels in both accuracy and efficiency, making it the optimal choice for our optical gate simulation software. This comprehensive performance comparison provides valuable insights into the suitability of each algorithm, emphasizing the supremacy of the Extra Trees Regressor for achieving our research objectives.

VI. The Power of Extra Trees Regressor

Our proposed methodology harnesses the formidable capabilities of the Extra Trees Regressor model, a leading-edge machine learning technique. Extra Trees Regressor stands out for its precision, efficiency, and versatility in regression tasks [49]. This ensemble learning method excels at capturing intricate relationships within data, enabling us to achieve unprecedented results in optical gate simulations. By utilizing the Extra Trees Regressor model, we significantly reduce the processing time, a perennial challenge in optical gate simulations. The model's ability to swiftly process large datasets and provide accurate predictions is invaluable. Additionally, it plays a pivotal role in optimizing the identification of optimal points, an essential aspect of gate simulations. The Extra Trees Regressor model's remarkable performance ensures that our proposed approach not only accelerates processing but also enhances the quality of output points. This section explores how this model contributes to the core of our research, setting the stage for innovative improvements in optical gate simulation software.

VII. Optimizing Optical Gate Outputs Using Extra Trees Regressor Predictions

The condition, defined as 'condition ← extratrees_preds_R10 < 0.3,' establishes criteria based on predictions derived from the Extra Trees Regressor model. This criterion scrutinizes whether the prediction output for input A equals input B within the gate (extratrees_preds_R10) and determines if it falls below 0.3. The variable 'optimize' assumes a multifaceted role in our optimization process, representing either the radius of the rods or the lattice constant. It plays a versatile role in defining the characteristics of the optical gate.

```
condition <- extratrees_preds_R10 < 0.3

for each prediction in predictions:

    if condition is true:

        diff = abs(extratrees_preds_R11 - extratrees_preds_R10)

        optimize <- (0.3 * diff) + (0.7 * extratrees_preds_R10)

    else:
        optimize <- NaN
```

The code snippet iterates through a set of predictions, performing calculations based on the previously defined condition.

- For each prediction in predictions:
  - The code evaluates if the condition is true (*if condition is true*:).
  - If the condition is true:
    - It calculates the absolute difference between the prediction outputs for scenarios where input when $A = B$ and when $A \neq B$, (*diff = abs(extratrees_preds_R11 - extratrees_preds_R10)).*
    - Then, it computes an optimized prediction value using a weighted average formula *(optimize <- (0.3 * diff) + (0.7 * extratrees_preds_R10)).* This calculation involves weighing the absolute difference and the prediction output for input A equals input B.
  - If the condition is not met:
    - It assigns NaN (Not a Number) to optimize. This assignment occurs when the condition *(extratrees_preds_R10 < 0.3)* is not satisfied.

This code segment essentially performs conditional calculations to determine an optimized prediction output based on the predictions obtained from the Extra Trees Regressor model, considering different scenarios within the optical gate.

VIII. Optimization of Optical Gate Parameters

In our pursuit of optimizing the optical gate's functionality, we focused on two pivotal parameters: the radius of the rods and the lattice constant. These parameters exert significant influence on the gate's behavior and output, thus necessitating thorough analysis and optimization.

A. Optimization based on Radius of the Rods

Table 3 displays the systematic exploration undertaken to determine the optimal radius value crucial for enhancing the gate's performance. After meticulous analysis, a specific radius of 0.05 was identified as a fundamental parameter for further evaluation. This chosen value played a pivotal role in guiding the evaluation process, utilizing the 'Optimize_R' column to elucidate the most optimal output states associated with this radius configuration.

Table 3 encompassed several essential columns, including:

- **x:** Represents the versatile parameter 'x', which plays a crucial role in shaping the behavior and configuration of the optical gate. This parameter 'x' embodies either the radius of the rods or the lattice constant, contributing significantly to the gate's performance and functionality.
- **extratrees_preds_R11:** Signifying the prediction output for the scenario where input A does not equal input B in the gate, derived from the ExtraTreesRegressor model.
- **extratrees_preds_R10:** Denoting the prediction output corresponding to the scenario where input A equals input B in the gate, derived using the same modeling approach.
- **Optimize_R:** This column encapsulates the optimized output values, calculated using a weighted formula based on predictions for scenarios when A =B and when A ≠ B, offering insights into the optimal output states for the gate concerning the radius of the rods.

A subset of the dataset illustrating parameter values and corresponding prediction outputs for the radius optimization is presented below:

TABLE 3: RADIUS OPTIMIZATION ANALYSIS

x	extratrees_ preds_R11	extratrees_ preds_R10	Optimize_R
0.0500	0.6200	0.1600	0.2500
0.0510	0.5768	0.1488	0.2326
0.0520	0.5336	0.1376	0.2151
0.0530	0.5012	0.1292	0.2020
0.0540	0.4472	0.1152	0.1802

B. Optimization based on Lattice Constant

Table 4 illustrates a parallel approach employed akin to the radius optimization process to identify the optimal lattice constant crucial for enhancing the gate's performance. Following thorough analysis, a lattice constant value of 0.12 emerged as the primary parameter necessitating further evaluation. This chosen value steered the evaluation process, utilizing the 'Optimize_X' column to outline the optimal output states associated with this lattice constant configuration.

TABLE 4: LATTICE CONSTANT OPTIMIZATION ANALYSIS

x	extratrees_ preds_R11	extratrees_ preds_R10	Optimize_X
0.1200	0.8216	0.1972	0.3254
0.1100	0.8132	0.1944	0.3217
0.1000	0.8000	0.1900	0.3160
0.0900	0.7860	0.1872	0.3107
0.0800	0.7600	0.1820	0.3008

These columns and their respective analyses form the cornerstone of our investigation, aiding in identifying optimal parameter settings for achieving desired output states within the optical gate.

IX. Simulation Results and Logical Inferences in Optical Gate Behavior through Optimization

Based on the results obtained from the optimization, the desired points are considered in the simulation. The points obtained as the final result are R0=R1=0.05μm and x=0.12μm. The simulation was done with this radius and displacement x values, and the results were obtained for different inputs. The simulation results are shown in Fig. 2.

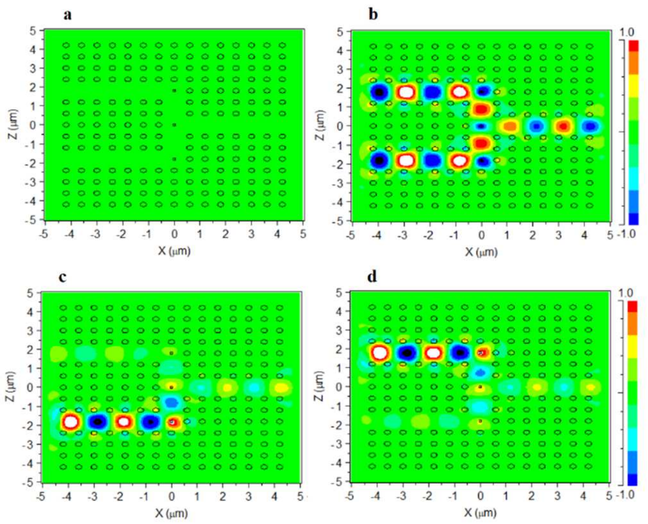

Fig. 2. Optical power distribution diagram for different input modes a) X=Y=0, b) X=Y=1, c) X=0, Y=1 and d) X=1 , Y=0

Fig . 2 shows that the output power has a high value only when both inputs are on, and in the other three modes, the output power is very weak, which is compatible with the AND gate. The simulation results show that in the first case, when both inputs are zero, the output is zero because there is no power in this case (see Fig. 2(a)).

In two cases where the inputs are not equal due to the symmetry of the structure, the power in both is the same and has a normalized value of 0.2 (see Fig. 2(c, d)). Finally, when both inputs are on, the power released to the output has a normalized value of 0.82, which can be considered logic 1. Table 5 shows the power values in different input modes.

TABLE 5. NORMALIZED POWER AND ITS LOGICAL VALUES IN DIFFERENT INPUT STATES

INPUT X	INPUT Y	Normalized Output	Logic Output
0	0	0.00	0
0	1	0.20	0
1	0	0.20	0
1	1	0.82	1

The contrast ratio parameter shows the power difference between modes 0 and 1. The value of the contrast ratio can be calculated from the relation $CR = 10 \times \log(\frac{P_{1,min}}{P_{0,max}})$. According to Table 5, the CR value is 6.1dB.

X. COMPARATIVE ANALYSIS OF PHOTONIC CRYSTAL OPTIMIZATION TECHNIQUES

A. Self-Collimation

Advantages: Self-collimation facilitates the creation of compact devices for optical integrated circuits, effectively addressing light coupling challenges. It provides high localization, tunability, and efficiency, heralding a new era in optical logic gate design.

B. Multi-Mode Interference (MMI)

Advantages: MMI devices are ideal for designing compact devices, offering high localization, tunability, and efficiency. They add versatility in tackling light coupling challenges.
Limitations: MMI designs may be constrained by speed and require in-phase input signals, which could limit their systematic designs.

C. Interference-Based Defect Methods

Advantages: The use of interference-based defects and resonance effects in cavity regions can boost coupling efficiency by controlling reflections and bending losses.
Limitations: These methods may have slow response times and require in-phase input signals, limiting their applicability in systematic design.

D. Nonlinear Kerr Effect

Advantages: Logic gates based on the nonlinear Kerr effect offer low response times and can be implemented using various optical components.
Limitations: They may operate within a narrow frequency range and require high power, which could impact gate speed and efficiency [50].

E. Strengths of the Presented Approach

This paper introduces a groundbreaking approach to optimizing AND gates in photonic crystals through machine learning, specifically using the Extra Trees Regressor model. This method offers several benefits:

1) Accuracy and Efficiency

The Extra Trees Regressor model exhibits high accuracy and efficiency in predicting output power, significantly improving the performance of optical gate simulation software.

2) Optimization Precision

Through detailed analysis, this research identifies optimal parameter settings for rod radius and lattice constant, which are crucial for achieving desired output states within the optical gate.

3) Machine Learning Integration

By incorporating machine learning techniques, this approach simplifies the optimization process and enables quick identification of optimal points, contributing to advancements in photonic crystal-based circuits.

F. Comprehensive Comparative Analysis

While other techniques have been explored in the literature, this paper distinguishes itself by providing a comprehensive comparative analysis of various optimization methods, highlighting the effectiveness of the proposed machine learning-based approach.
In conclusion, this research presents an innovative methodology that not only addresses existing challenges in photonic crystal-based logic gate design but also provides novel insights into optimization techniques. This underscores the potential for significant advancements in optical circuitry and information transmission systems.

XI. CONCLUSION

This paper presents a novel approach to optimizing the performance of AND gates using machine learning techniques. By leveraging the power of ExtraTreesRegressor, we significantly improved the accuracy and efficiency of optical gate simulation software. This approach enables us to rapidly identify optimal parameter settings for achieving desired output states within the optical gate. Additionally, the meticulous optimization of rod radius and lattice constant unveils their profound influence on gate functionality, with specific parameter configurations yielding desired output states akin to an AND gate. Our findings demonstrate that the Extra Trees Regressor model is a valuable tool for optimizing optical gate performance. Additionally, it plays a pivotal role in optimizing the identification of optimal points, an essential aspect of gate simulations. The ExtraTreesRegressor model's remarkable performance ensures that our proposed approach not only accelerates processing but also enhances the quality of output points. Overall, this research demonstrates the efficacy of machine learning in augmenting photonic crystal-based circuits, paving the way for advancements in information transmission and logical operations within electronic systems.

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