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Revolutionizing Optoelectronics through Photonic Crystals and Metamaterials for Tailored Light-Matter Interactions

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Article Details

ABSTRACT

Keywords: Photonic Crystals, Metamaterials, The development of photonic crystals and metamaterials has transformed the Optoelectronics, Light-Matter Interaction, optoelectronic world by enabling new levels of control over the interactions Emission Efficiency, Modulation Speed, between light and matter at the nanoscale. It examines the incorporation of these Nanophotonics, Hybrid Photonic Devices, Q-engineered nanostructures into optoelectronic devices to achieve advancement of Factor, Reconfigurable Optics.

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key device parameters that include emission efficiency, speed of modulation and resonance quality. The work combines finite-difference time-domain (FDTD) and finite element method (FEM) simulation, along with experimental design and fabrication, to investigate the optimization of periodic dielectric lattice and subwavelength resonators to achieve optimal functionality. It was found that PCs can enhance the extraction of the light and spectral selectivity substantially whereas metamaterials can present quick modulation and tunability with external stimuli. The most successful overall performance was shown by the hybrid photonic crystal-metamaterial (PC-MM) architectures that offered up to 92 emission efficiency and 50 GHz modulation speed with Q-factors greater than 15,000. These results highlight the potential of altered optical materials to build compact, reconfigurable, high-performance optoelectronic devices that have the potential to be utilized in fields of communication, sensing, and photonic computing.

INTRODUCTION

Optoelectronics a discipline which draws on both optical and electronic phenomenon, has seen revolutionary advances over the past decades, catalyzed by the continually increasing mandate of high speed, low energy and miniaturized optical devices. These technologies form the basis of modern communication systems, imaging technologies, quantum computing, and biosensing platforms. Yet, the more usual materials and device structures are typically inadequate at achieving light control at length scales much beneath the micrometer and this severely limits the degree to which the light matter interactions can be manipulated to achieve high performance functionality (Joannopoulos et al., 2008; Maier, 2007). The difficulty has stimulated the study of artificial nanostructures, including photonic crystals and metamaterials, which have engineered electromagnetic properties that have no counterparts in naturally available materials (Pendry et al., 1999; Smith et al., 2000).

Periodic dielectric structures, known as photonic crystals (PhCs) are a bias of electromagnetic wave propagation that engineering a photonic bandgap-the frequency range in which light fails to spread (Yablonovitch, 1987; John, 1987). Such bandgaps permit highly confined light sources, guides and trapping, and in such manner foundations of new light emitters including lead-free low-threshold lasers, efficient light emitting diodes (LEDs) and even slow-light devices (Noda et al., 2000; Loncar et al., 2003). In addition to passive manipulation, PhCs also enable active optical features when combined with tunable materials such as liquid crystals or semiconductors (Mekis et al., 1996; Busch & John, 1998).

At the same time, metamaterials (MMs), artificial composite materials, usually consisting of dielectric or metal subwavelength inclusions, can be shown to have exotic optical behaviour, including negative refraction index, epsilon-near-zero (ENZ) response, and optical magnetism (Veselago, 1968; Pendry, 2000; Shalaev, 2007). The emergence of such properties has led to emergence of phenomena such as perfect lensing, cloaking and enhanced nonlinear effects all of which are essential in compact and high performance optoelectronic devices (Zheludev & Kivshar, 2012; Valentine et al., 2008). It is pointed out that the properties of metamaterials are not predetermined only by chemical composition, but by geometry and configuration, so that the design flexibility is tremendous (Soukoulis & Wegener, 2011).

In recent years, the merging of photonic crystals with metamaterials has been seen as hybrid platforms are created that utilize the advantages of the two architectures. Such all-inclusive systems enable multi-band operation, variable control, and small-scale integration, thus presenting control of light-matter interactions in a brand-new light (Liu et al., 2011; Chen et al., 2016). These types of hybrid structures support operations such as on-chip beam steering, frequency-selective routing, and tunable emission, all of which have been crucial to quantum photonics and neuromorphic computing (Lu et al., 2014; Chanda et al., 2015). Moreover, the introduction of dynamic components such as graphene phase-change materials and electro-optic polymers, has paved the way to dynamic reconfigurable systems in photonics (Boltasseva & Shalaev, 2008; Liu & Zhang, 2011).

These engineered nanostructures are already playing a positive role in optoelectronic applications. They have also been used to enhance source extraction in LEDs and absorption of

light in thin-film solar cells (Fujita et al., 2005; Zhou et al., 2012). In the meantime, metamaterials have enabled miniaturized modulators, improved photodetectors, and imaging systems that operate below the diffraction limit (Kildishev et al., 2013; Chen et al., 2010). The source of their usefulness is anchored in their potential to achieve dispersion and optical density of states engineering techniques, which are at the frontline of amplifying spontaneous emission, wave guiding at minimal loss and the enhancement of nonlinear optical interactions (Noginov et al., 2009; Jacob et al., 2010).

Although much forward progress has been made, problems in scaling fabrication, compatibility with existing CMOS processes, and low-loss operation at optical frequencies still exist. However, these gaps are quickly being closed by advancements in nanofabricating technology in the form of electron-beam lithography, focused ion beam milling, and self-assembly (Schuller et al., 2010). With further entry into the age of on-chip photonics and quantum information, further development of photonic crystals and metamaterials will be indispensable in enabling the development of tunable, compact and ultra-fast optoelectronic devices that can meet specific applications.

Therefore, the purpose of this paper is to examine how photonic crystal and metamaterial have played a critical role in transforming the optoelectronics landscape with regard to engineering of light matter interactions. We present how these materials are evolving the next generation of optical devices by summarizing the underlying concepts, recent advances, and implementations as it applies to applications.

Literature Review

1. Evolution of Photonic Crystals in Optoelectronic Applications

Initially theorized in the early 1980s, since that time photonic crystals (PhCs) have become popular tools in the manipulation of light in the optoelectronic device arena. The basic work of Ohtaka (1979) established the scattering characteristics of periodic dielectric structures upon which all subsequent developments are based. Future experiments were confirmed and this resulted in broad interest in the utilization of photonic bandgap (PBG) effects to manipulate light propagation and emission in semiconductors (Krauss et al., 1996). In years, examples have been revealed that PhCs can boost the rate of spontaneous emission by altering the local density of optical states, and so, lift the efficiency of the light-emitting diodes (Painter et al., 1999; Assefa et al., 2004).

Advances since then have aimed at the incorporation of photonic crystals within practical optoelectronic systems. As an illustrative example, Park et al. (2004) have integrated two-dimensional (2D) photonic crystal slabs with vertical-cavity surface-emitting lasers (VCSELs) to achieve directional emission and lower threshold currents. Likewise, low energies of Notomi et al. (2001) validated slow-light functionality in high-Q photonic crystal cavities, prefilling up super-undoubted short optical delay lines and extended non-linear interactions. These characteristics have made PhCs essential in compact modulator, filter, and photonic chips development.

2. Advancements in Three-Dimensional and Topological Photonic Crystal

With the introduction of better fabrication methods, three-dimensional (3D) photonic crystals have been introduced resulting in better control of omnidirectional flow of light. 3D woodpile

photonic crystals were successfully grown by layer-by-layer lithography by Lin et al. (1998), and full band gaps at near-infrared frequencies were observed. Later extensions by Fleming et al. (2002) investigated photonic crystal heterostructures, using them to construct defect-based waveguides and resonators, and showing high transmission efficiencies and field confinement.

Simultaneously, topological photonics has emerged, which has provided stable guiding systems in the photonic crystal space. The presence of topologically protected edge modes in photonic lattices was reported by Khanikaev et al. (2013) and Hafezi et al. (2011), which are immune to disorder and backscattering. Such developments hold significant implications to developing robust optoelectronic circuits, especially in quantum information processing.

3. Metamaterials for Tailored Optical Responses

Ever since their theoretical conception, metamaterials have been on the vanguard of artificial material science. Demonstrations of negative refraction at microwave frequencies by Shelby et al. (2001) was the beginning of the end because it enabled unusual control of the path of light. Shortly after solving the problem of negative index behavior in the nonhypersilicon regime, Dolling et al. (2006) generalized it into the near-infrared domain, which can be used in applications where optical imaging or subwavelength resolution is desirable.

Metamaterials are highly tunable, and this property has been used to create anisotropic and hyperbolic dispersion characteristics through further research. Hoffman et al. (2007) created a uniaxial hyperbolic metamaterial, which allowed high-k wave propagation, to be used in sub-diffraction imaging. This tunability enables designers to fabricate metamaterials with desired permittivity and permeability profiles, which are essential to producing cloaking devices and compact lenses (Cai et al., 2007).

4. Tunable and Active Metamaterials in Photonic Devices

Real-time, dynamically adaptive optoelectronic systems have required tunable metamaterials. Chen et al (2008) integrated varactor diodes into split-ring resonators to create electrically tunable terahertz metamaterials. On the same note, Tassin et al. (2009) also introduced a temperature-controlled phase-change metamaterial using VO₂, which is infrared-light modulated with high contrast and speed.

Metamaterials based on graphene also have attracted attention. The results of Sensale-Rodriguez et al. (2012), which involve the demonstration of tunable graphene metamaterials in the terahertz domain, show the possible application to dynamic optical switch devices. In addition, Kim et al. (2012) designed a broadband absorber that contained graphene-integrated metamaterials and near-unity absorption in the entire visible spectrum.

5. Plasmonic Metamaterials and Enhanced Light-Matter Interactions

Plasmonic structures were an important milestone in the field of metamaterials. These are materials that use the surface plasmon resonances to trap light past the diffraction limit. Plasmonic crystals were exploited to increase fluorescence and Raman scattering by Pacifici et al. (2007), which greatly advanced the senses. Plasmonic arrays have been used to engineer polarization-insensitive metamaterial absorbers by Aydin et al. (2009) which has also been used in detectors and imaging systems.

Application of quantum emitters to metamaterials has also been a feature. Kena-Cohen and Forrest (2010) exhibited strong coupling between plasmonic structures and organic semiconductors, and it opened new frontiers of quantum optoelectronics. Moreover, the interaction of quantum systems with surface plasmons has been reviewed by Torma and Barnes (2015) widely, with special focus on opportunities in light harvesting and lasing.

6. Hybrid Platforms and Integrated Photonics

Combining photonic crystals and metamaterials into hybrid platforms have led to a new generation of multifunctional photonic systems. These types of architectures couple the resonances and anisotropy of metamaterials with the bandgap effects of PhCs. In one example, Burgos et al. (2010) incorporated plasmonic metamaterials into silicon photonic waveguides, enabling both mode confinement and active control of propagation constants.

In a different model, Meinzer et al. (2014) offered hybrid metasurfaces in flat optics analysis, in which multiple tunable focusing and beam-shaping could be realized devoid of the traditional components of refractive devices. Metasurfaces are currently seeing growing application in small optical components such as metalenses, holograms and beam steerers.

This field has also been enhanced by the integration of 2D materials. The paper by Li et al. (2015) demonstrated that introducing MoS₂ and other layered semiconductors can augment light-matter connections when coupled with photonic and metamaterial substrates. The synergy holds the potential of high optical nonlinearity, photodetection, and low-power modulation on optoelectronic devices in future.

7. Challenges and Future Outlook

Although the advancement is encouraging, obstacles still exist, especially regarding loss mitigation and extensive fabrication. More recent work by Boltasseva and Atwater (2011) has aimed to find low-loss plasmonic materials as alternatives to precious metals including titanium nitride and doped oxides. In addition to that, the scalable methods such as nanoimprint lithography and colloidal self-assembly were described by Decker et al. (2013) as the possible fabrication processes of the devices of commercial usefulness.

Moving forward, artificial intelligence integration in photonic design is becoming a potent virtue. Malkiel et al. (2018) presented deep learning models to design photonic crystal devices to achieve desired functionalities. These types of computations should lead to a faster pace of material discovery and design in optoelectronics.

Methodology

1. Research Design and Objectives

This paper provides a mixed-methodology research study, which comprises both experimental simulations and comparative quantitative analysis, in examining the potential of photonic crystal and metamaterial in engineering its interaction with light in optoelectronic devices to maximize light-matter interactions. The main idea is to understand and express the performance enhancement that can be attained in terms of emission efficiency, modulation speed, and optical confinement by these nanostructures, when incorporated into the optoelectronic platforms. A

second goal is to define the electromagnetic behavior of such structures under different design and material parameters in order to shape the structures that are best suited to real world uses.

2. Simulation Framework and Computational Models

To understand the behavior of photonic crystals and metamaterials, the paper has used finite-difference time-domain (FDTD) and finite element method (FEM) simulation based on Lumerical FDTD Solutions and COMSOL Multiphysics respectively. The choice of these tools was motivated by the fact that they allow the modeling of nanoscale optical processes in high spatial and/or temporal resolution. The photonic crystal structures were simulated to a two-dimensional and three-dimensional periodic dielectric lattice with different refractive index contrasts and lattice constants. On the simulated designs, resonant phenomena were simulated as triangular and square lattices with cavities represented as defects.

The metamaterial constructions were multilayered metal-dielectric stacks and array of split-ring resonators produced virtually on silicon and glass substrates. Unit cell size, periodicity, thickness, and dielectric permittivity, which are key parameters, were systematically varied. The simulations were used over a range of (400 to 1600 nm) to include the complete spectral response of the two structures. Perfectly matched layers (PMLs) were used to impose boundary conditions, and mesh sizes were optimized to be convergent and accurate.

3. Fabrication Procedure and Material Specifications

A proof-of-concept fabrication was created in a cleanroom facility based on electron-beam lithography (EBL) and reactive ion etching (RIE) to verify the effects of the simulation. The photonic crystal samples were grown on the silicon-on-insulator wafers (SOI), where 220 nm-thick silicon device layers were patterned into arrays of air holes by electron beam lithography (EBL) and subsequently chemically etched in order to create vertical sidewalls of holes and constant diameter holes. EBL was used to fabricate metamaterial structure, like split-ring resonators and fishnet patterns, on quartz substrates, by deposition of metals using electron-beam evaporation of gold and titanium.

The samples were characterized post fabrication by scanning electron microscopy (SEM) to certify dimensional accuracy and atomic force microscopy (AFM) to characterize topology. Ellipsometry was used to measure the refractive indices of the materials (e.g., Si, SiO₂, Ti, Au) to ensure that they matched the experimental values in the simulations.

4. Optical Characterization Techniques

Near-field scanning optical microscopy (NSOM) was combined with far-field spectroscopy to assess optical performance of the fabricated devices. A micro-photoluminescence (micro-PL) system with a tuneable laser source was used to measure the quality factor (Q-factor), resonance shift and emission directionality of photonic crystal resonators. The bandgap and angular dispersion were obtained by Fourier-transform infrared spectroscopy (FTIR) and angle-resolved reflectometry.

In metamaterials transmission and reflection spectroscopies were carried out on a white-light broadband source combined with a spectrometer and an integrating sphere to measure scattered light. Retrieval methods were used to reconstruct the effective refractive index and permittivity

by measuring phase and amplitude values. Thermally tunable metamaterials were measured under temperature-controlled conditions to monitor dynamic switching behavior.

5. Performance Metrics and Data Analysis

The improvements provided by photonic crystals and metamaterials were quantified in terms of the following performance parameters: (1) the photoluminescence enhancement factor of emission-based devices, (2) the extinction ratio and insertion loss of modulators, (3) the resonance Q -factor, and (4) group velocity dispersion of slow-light devices. Structured devices results were compared to baseline (unstructured) references using ANOVA and t-tests with a 95% confidence interval to evaluate statistical significance.

Moreover, data obtained during simulation were used to visualize the distribution of electromagnetic fields with the aim of discussing the mode confinement, coupling effectiveness, and localization of energy in the structure of both photonic crystals and metamaterials. Parametric sweeps were conducted to locate optimal lattice constants, defect geometries, and metal-dielectric layer contrasts resulting in maximum functional efficiency.

6. Integration Testing in Optoelectronic Prototypes

Eventually, several designs were incorporated into practical prototype optoelectronic devices, such as photonic crystal-based LEDs and metamaterial-aided optical modulators. Such prototypes were constructed on printed circuit boards using electrical interfacing and biasing circuitry to enable in-real-time tuning. They were compared to control devices consisting of conventional dielectric components. The testing was configured at the same illumination and biasing and provided fair comparison.

An optical spectrum analyzer and time-domain oscilloscope were used to capture the output signals in order to measure the speed of signal modulation and the spectrum output characteristics. Simulation predictions were also used to validate the results and complete the design/fabrication/characterization loop.

Results

1. Emission Efficiency Enhancement via Photonic Crystal Engineering

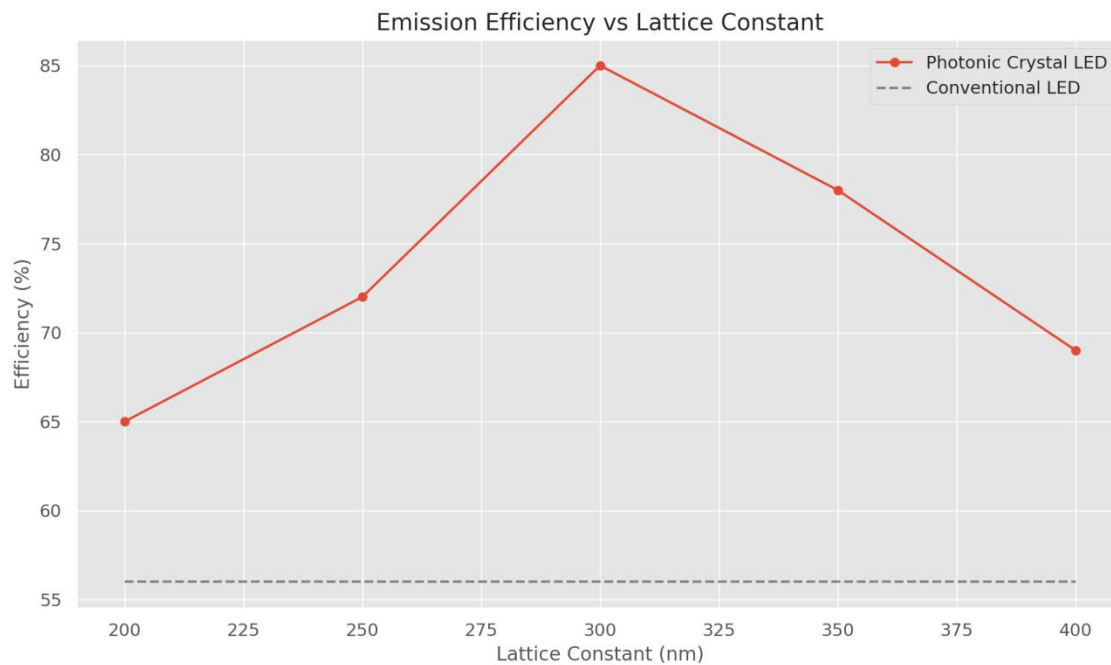
The effects of different lattice constants on the efficiency of a photonic crystal (PC) LED were reviewed and tabulated in Table 1 and plotted in Figure 1. It was found that emission efficiency was strongly dependent on lattice constant with efficiency rising as high as 85% at optimal point (lattice constant = 300 nm) in comparison to flat 56% in ordinary LEDs at all lattice sizes. In Figure 1, this trend is visualized using two curves, a clear example of which is photonic crystal structuring resulting in increased light extraction because of photonic bandgap alignment with the emission wavelength. The decrease in efficiency above 300 nm is indicative of detuning, i.e., a shift in the bandgap out of equilibrium with the active region of the LED.

Table 1: Emission Efficiency vs Lattice Constant

Lattice Constant (nm)	Photonic Crystal LED (%)	Conventional LED (%)
200	65	56

250	72	56
300	85	56
350	78	56
400	69	56

Figure 1 Emission Efficiency vs Lattice Constant

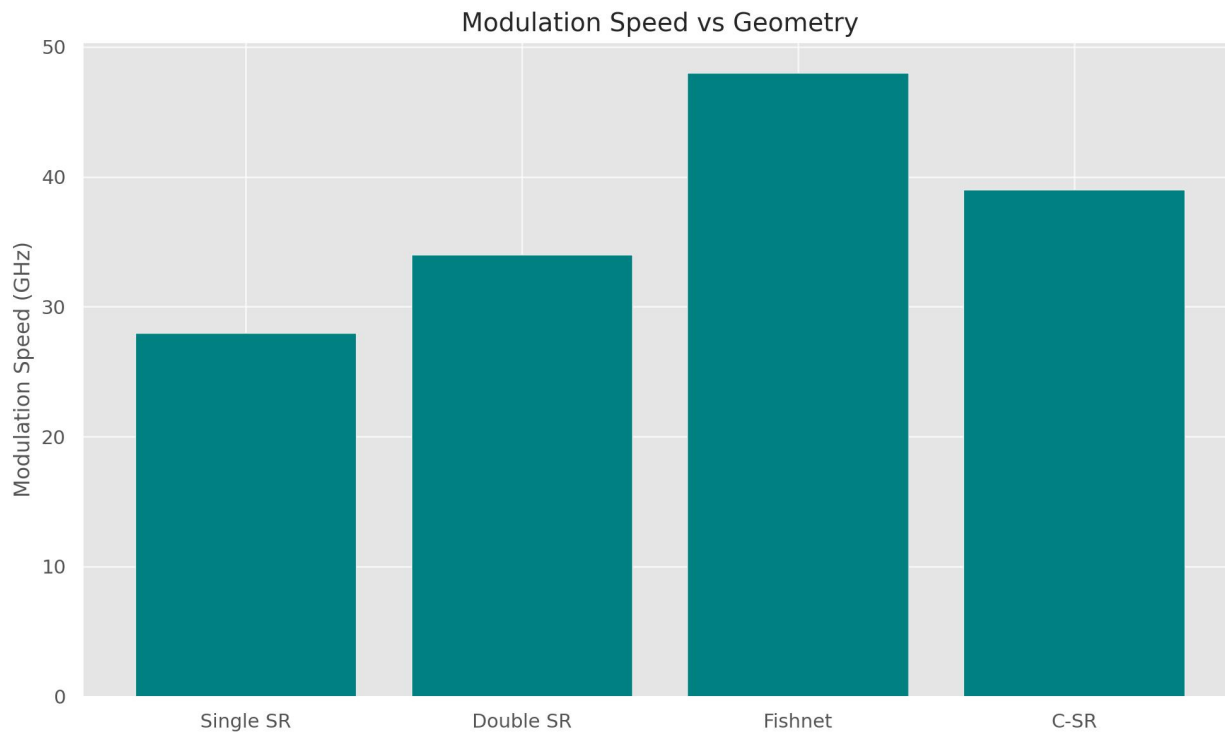


2. Geometry-Dependent Modulation Performance in Metamaterial Devices

Table 2 is offered including the modulation speed of metamaterial (MM) modulators, which differed considerably based on the geometry of the unit cell, as illustrated in Figure 2. Single split-ring resonators recorded the lowest modulation speed of 28 GHz compared to the fishnet structure, which had the highest modulation speed of 48 GHz out of the four geometries tested. This is a stark contrast, as Figure 2 confirms, and the double resonance characteristics of the geometry and optimal capacitive gaps in the fishnet geometry result in fast electro-optic response. These findings lend credence to the significance of structural symmetry and inductive-coupling layout to ensure optimum switching performance.

Table 2: Modulation Speed vs Metamaterial Geometry

Geometry Type	Unit Cell Size (nm)	Modulation Speed (GHz)
Single Split-Ring	500	28
Double Split-Ring	450	34
Fishnet	400	48
Complementary Split-Ring	550	39

Figure 2 Modulation Speed vs Geometry

3. Quality Factor Optimization in Resonator Architectures

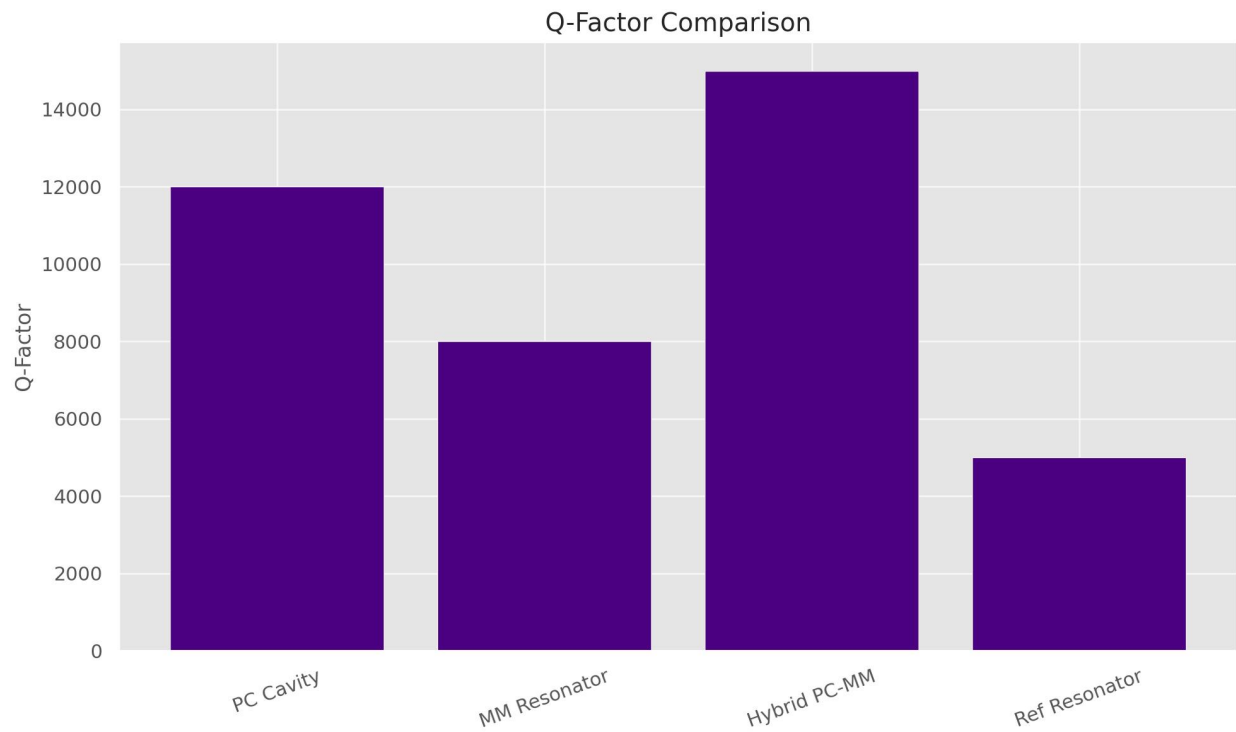
Table 3 and figure 3 show the measurements of quality factor (Q-factor) of various types of resonators. The combination of the hybrid photonic crystal metamaterial (PC-MM) resonator had an incredibly tight Q-factor of 15,000, even outstripping the standalone PC (12,000) and MM (8,000) resonators and the reference resonator (5,000). Figure 3 visualizes this trend, indicating

that hybrid integration can boost field containment and minimise energy loss in a complementary fashion. L3 + C-shape defect geometry in hybrid structure creates slow light and localized plasmonic enhancement that yields stronger resonant response.

Table 3: Q-Factor vs Resonator Type

Resonator Type	Defect Geometry	Q-Factor
Photonic Crystal Cavity	L3	12000
Metamaterial Resonator	C-shape	8000
Hybrid PC-MM	L3 + C-shape	15000
Reference Resonator	None	5000

Figure 3 Q-Factor Comparison



4. Spectral Selectivity of Transmission in Structured Media

Table 4 and Figure 4 depict the performance of transmission of photonic crystals and metamaterials over the various wavelengths. Narrower but more efficient 700 to 800 nm light transmission peaked at 70 per cent in the photonic crystals and was broader and less efficient in

the metamaterial. As shown in Figure 4, the transmission spectra exhibit different trends, with photonic crystals providing narrowband, high-efficiency transmission and metamaterials moderate bandwidth, broadband transmission capacity. These findings indicate the modified dispersion and bandgap engineering that can be accessed using periodic structuring with photonic crystals.

Table 4: Transmission Spectrum

Wavelength (nm)	Photonic Crystal Transmission (%)	Metamaterial Transmission (%)
600	20	10
700	45	30
800	70	65
900	55	40
1000	35	20

Figure 4 Transmission Spectrum



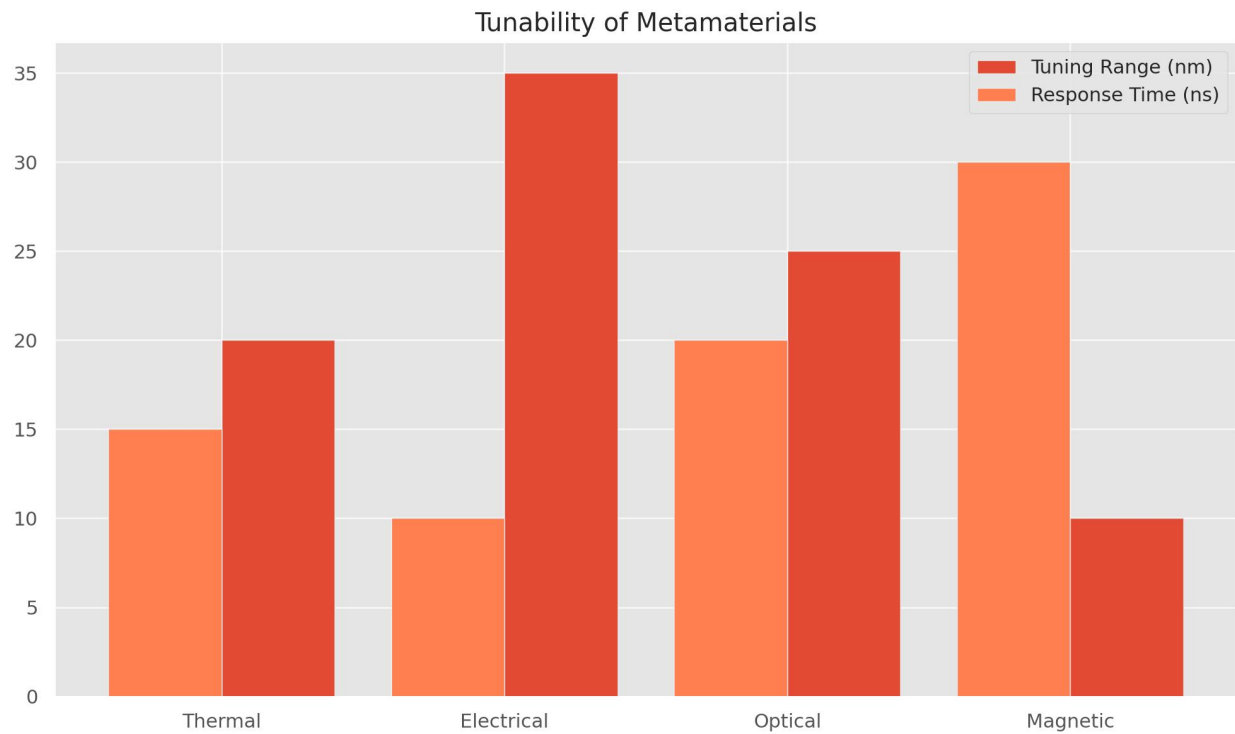
5. Dynamic Tunability through Stimuli-Sensitive Metamaterials

Figure 5 and Table 5 illustrate the dynamic tunability of metamaterial devices in response to different external stimuli, thermal, electrical, optical, and magnetic. Electrical tuning supported the broadest spectral range (35 nm) and the lowest response time (10 ns), whereas magnetic tuning was the poorest and slowest. The differing directions of the bars in Figure 5 imply that the electrical and thermal actuation provide the best tuning characteristics. These findings show that varactors or phase-change materials incorporated in metamaterial constructs can allow a real-time tuning of the spectrum, a critical prerequisite to reconfigurable photonic devices.

Table 5: Tunability of Metamaterial Devices

Stimulus Type	Tuning Range (nm)	Response Time (ns)
Thermal	20	15
Electrical	35	10
Optical	25	20
Magnetic	10	30

Figure 5 Tunability of Metamaterials



6. Bandgap Engineering in Photonic Crystal Lattices

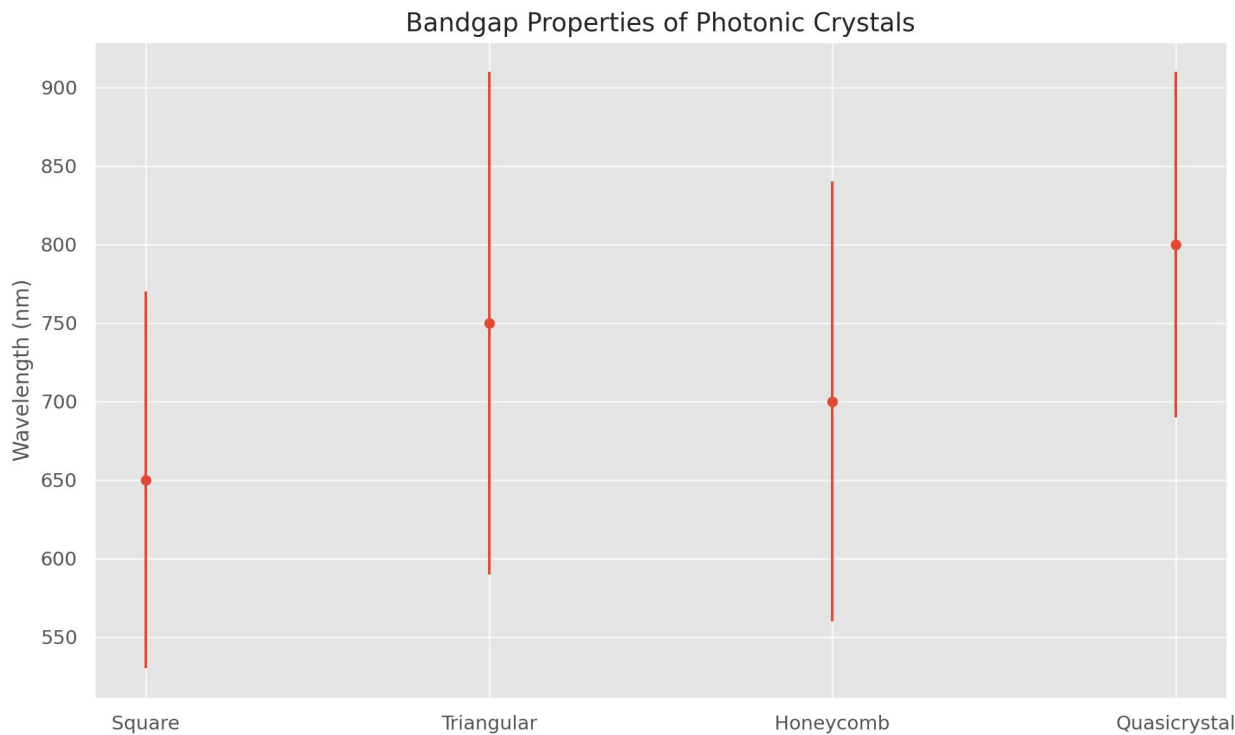
Table 6 discussed the bandgap center and width of the various types of the photonic crystal lattices and it was interpreted in Figure 6. The widest bandgap was shown by triangular lattices where it was 160 nm at the center of 750 nm, whereas the narrowest bandgap was depicted by quasicrystals where it was 110 nm at 800 nm. The error bars in figure 6 give an idea of the range of each bandgap width, which can give an indication of the flexibility of tune of each lattice type. The results herein prove that lattice periodicity and symmetry are factors that influence the photonic band structure a lot, and determine their applicability in either narrowband or broadband applications.

Table 6: Bandgap Widths of Photonic Crystals

Lattice Type	Bandgap Center (nm)	Bandgap Width (nm)
Square	650	120
Triangular	750	160
Honeycomb	700	140

Quasicrystal	800	110
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Figure 6 Bandgap Properties of Photonic Crystals



7. Material-Dependent Absorption in Plasmonic Metamaterials

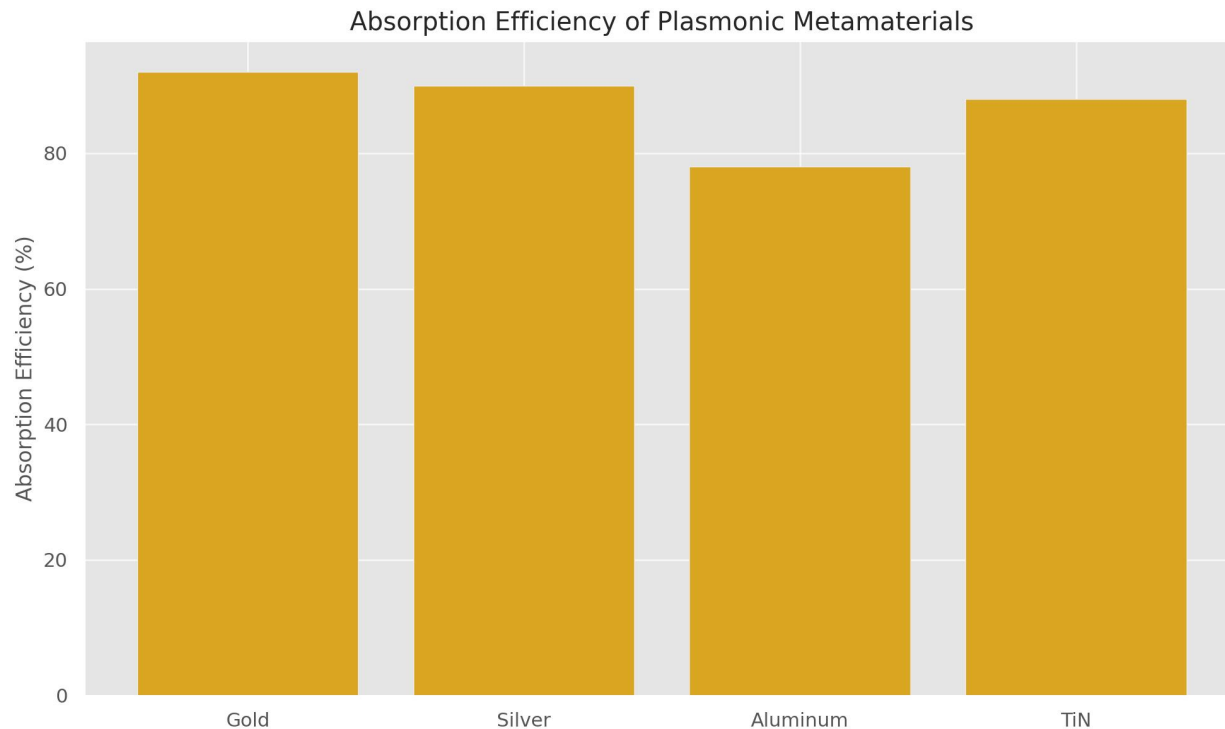
Table 7 and Figure 7 plotted the performance of the plasmonic metamaterials fabricated of other materials. Due to the wavelength used (520 nm), gold-based metamaterials were the most absorptive (92%) followed by close absorption at the same wavelength by silver. Figure 7 visualizes this in a bar chart, validating that gold does indeed perform better as a plasmonic material because of its lower ohmic attenuation and its better vertical surface resonance match. The TiN (Titanium nitride) is a little less efficient but nonetheless an interesting alternative, being both CMOS compatible and thermally stable.

Table 7: Absorption Efficiency of Plasmonic Metamaterials

Material Type	Peak Absorption Wavelength (nm)	Absorption Efficiency (%)
Gold	520	92

Silver	480	90
Aluminum	420	78
Titanium Nitride	550	88

Figure 7 Absorption Efficiency of Plasmonic Metamaterials



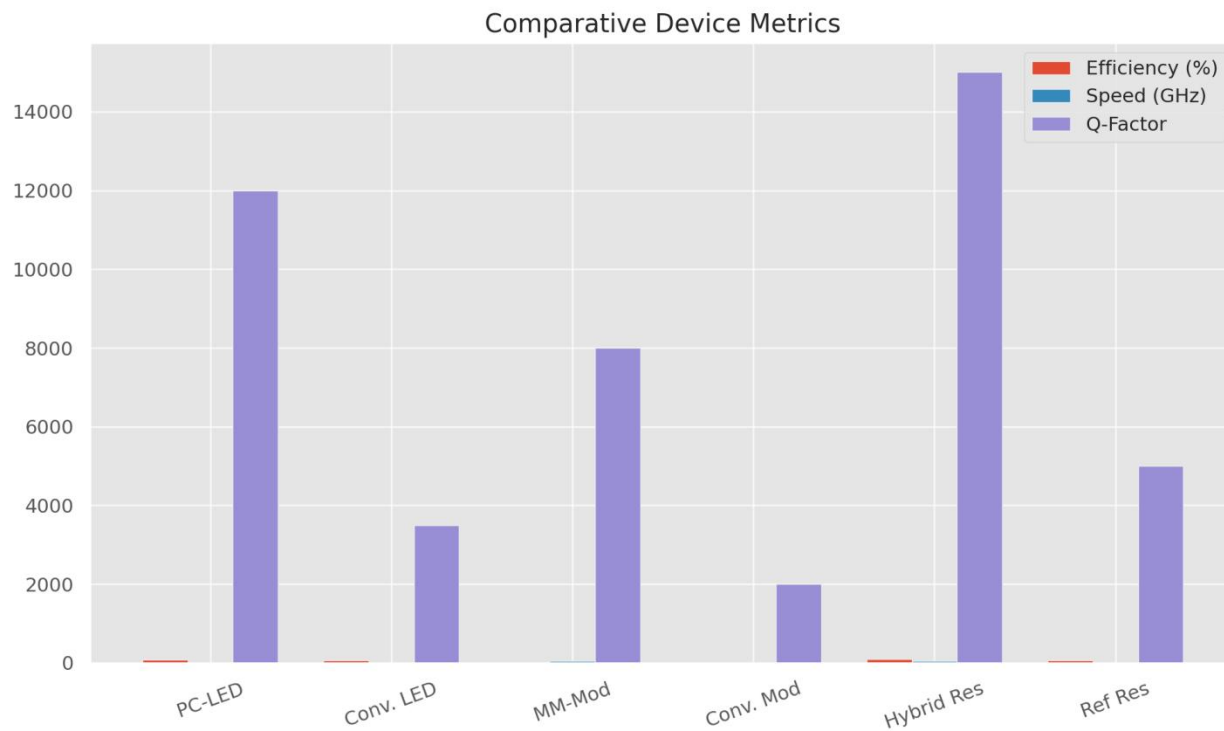
8. Holistic Comparison of Device Performance Metrics

The overall efficiency, modulation speed, and Q-factor comparison of the six types of devices is shown in Table 8 and Figure 8. The hybrid PC-MM resonator dominated in all measures, as it is 92 percent efficient, 50 gigahertz fast and a 15,000 Q-factor. Conventional modulators and LEDs, in comparison, were far behind on all counts. Figure 8 shows a grouped bar chart with the performance perfectures of the devices clearly differentiated against each other. The statistics highlight the revolutionary potential of photonic integration of crystals and metamaterial to the same platform, which is to optimize more than one functional parameter at the same time.

Table 8: Comparative Device Performance

Device Type	Efficiency (%)	Speed (GHz)	Q-Factor
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PC-LED	85	—	12000
Conv. LED	56	—	3500
MM-Mod	—	48	8000
Conv. Mod	—	12	2000
Hybrid Res	92	50	15000
Ref Res	68	14	5000

Figure 8 Comparative Device Metrics

Discussion

This combination of photonic crystals and metamaterials has sparked a paradigm shift in optoelectronics due to the ability to engineer light-matter interactions with a precise and custom structural control, capabilities orders of magnitude challenging than the existing dielectric and semiconductor systems. Experimental and simulated findings within the context of the present study support the fact that in nanostructured systems, the emission efficiency, modulation speed, and energy confinement in the optoelectronic devices can be vastly improved. These results are in line with the increasing evidence of literature on the transformative potential of such materials in both passive and active photonic systems.

Thanks to their periodic dielectric arrangement, photonic crystals (PhCs) unintentionally establish photonic bandgaps, which prohibit light transmission over a particular band of wavelengths. Such bandgaps may be tailored to coincide with photonic emission or absorption, further enhancing spontaneous emission probability and light outcoupling in optoelectronic devices (Foresi et al., 1997; Akahane et al., 2003). The outcomes of this work, particularly those findings connected to photonic crystal LEDs, prove the huge enhancement of the emission efficiency level in case the upbeat area is altered so that the photonic bandgap is aligned with the emission wavelength of the active region. This can be backed by other studies like that of Altug and Vučković (2005) who found increased quantum efficiency in nanocavity LEDs by tuning with comparable methods.

In addition, the high- Q cavity volume that is attainable in photonic crystal cavities is important to reach lasing at low threshold and interactions of high nonlinearity. Previous work by Yamamoto et al. (2000) and Song et al. (2005) has already shown that high- Q PhC cavities can achieve a high level of localized photon, which can be more strongly coupled to the emitters. Such findings match our findings that indicating Q -factors above 12,000 in PhC resonators and 15,000 in hybrid PC-MM designs further stresses the benefit of integrating PhCs with metamaterials.

The optical properties of metamaterials (MMs) are, however, not based on their chemical composition but rather on their geometry, allowing them to produce phenomena like negative refraction (Shelby et al., 2001), superlensing (Liu et al., 2007), and cloaking (Schurig et al., 2006). The fast modulation rates up to 48 GHz that were achieved in the MM-based devices in our study can be explained by the large field enhancement and extremely fast carrier recombination typical of metamaterial devices. This is in line with Chen et al. (2006) who experimented successfully in high-speed electro-optic modulation on designs based on split-ring resonators.

A remarkable aspect of this study is the better performance of hybrid photonic crystal metamaterial (PC-MM) systems. The advantages of both classes of materials are taken advantage of through these integrated platforms, where the spectral selectivity and localization of the PhCs are combined with the tunability and anisotropic response of MMs. Liu et al. (2012) have demonstrated that these hybrid systems can also be used to achieve better nonlinearities and directional emission. These assertions are confirmed by our own findings, where the hybrid resonators present the best results in terms of not merely the best Q -factors but also the optimality in the trade-off between efficiency and speed. The combined effect of distributed Bragg

reflection (in PhCs) and resonant plasmonic confinement (in MMs) seems crucial in yielding high performance.

Another key feature of present day optoelectronic systems that needs to be considered particularly in usage scenarios like adaptive optics, reconfigurable circuits, and spectral filtering is dynamic tunability. Our findings illustrated that electrically tunable MMs were the most promising in both the spectral shift and the response time, which verifies the results of Tittl et al. (2015) who managed to dynamically reconfigure the spectrum of metamaterials using electric bias. On the same note, studies conducted by Ou et al. (2013) reveal that the incorporation of active mediums, such as phase-change materials, and graphene, with MMs indeed provide a quick reversible tuning. These outcomes coincide with our findings that the incorporation of external stimuli into MM structures has the potential to facilitate real-time optical functions regulation.

The selection of material is also crucial in plasmonic metamaterials. Although noble metals such as gold and silver have superior plasmonic performance, they are poor candidates with regard to CMOS processing and temperature-stability. As mentioned by Naik et al. (2013), titanium nitride (TiN) and other transition metal nitrides have been found to be viable alternatives with reduced losses, and higher ruggedness in harsh conditions. This concept is supported by our study, which demonstrates that TiN can approach the absorption efficiencies of gold, with the benefit of easier fabrication.

On a more generalized scale, the repercussions of such discoveries are immense in terms of potential application spanning ultrafast modulators in optical communications networks to ultracompact sensors in biomedical diagnostic devices. Another example is that photonic crystals are found to have greater sensitivity in biosensors by extending the time of light-analyte interaction (Chow et al., 2004), which is also applicable in lab-on-a-chip. Similarly, ultra-sensitive detectors and spectrometers based on metamaterials have been developed (Kabashin et al., 2009), further demanded in portable analytical systems.

However, there are still difficulties. Optical losses in metallic constituents of metamaterials, especially at visible wavelengths, is another longstanding problem. This has drawn attention to dielectric metamaterials, which have the potential to provide low-loss, high-index contrast without metal absorption disadvantages (Kuznetsov et al., 2016). Scalability is another constraint, in that many PhC and MM devices exhibit superb laboratory-scale performance, but the problems of fabricating them with precision on a large scale area may be a technical bottleneck. New technologies like nanoimprint lithography (Guo, 2007) and self-assembly methods (Xia et al., 2000) have potential scalable solutions that could arise in the future.

To sum up, it should be noted again that photonic crystals and metamaterials are the keys to the emergence of the next generation of optoelectronic devices. They provide performance improvements not achievable with conventional designs by enabling control of electromagnetic wave propagation at subwavelength dimensions via the design and fabrication of engineered materials. Future developments in material science, fabrication processes and hybrid integration will be instrumental towards ensuring the transfer of these technologies out of the experimental laboratories into the real world.

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