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[Stoyan Tanev](#) * and [Samantha Sieklicki](#)

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Article

Using topic Modeling as a Semantic Technology: Examining Research Article Claims to Identify the Role of Non-Human Actants in the Pursuit of Scientific Inventions

Stoyan Tanev * and Samantha Sieklicki

Technology Innovation Management Program, Sprott School of Business, Carleton University, Ottawa, ON, Canada K1S 5B6

* Correspondence: stoyan.tanev@carleton.ca

Abstract: Actor-network theory (ANT) represents a research paradigm that emerged within science and technology studies by explicitly focusing on the contingency of scientific inventions and the role of non-human actants in the invention course of action. The article adopts an ANT perspective to focus on the invention of Sub-Wavelength Grating (SWG) photonic metamaterials by the members of a research group in the National Research Council (NRC) of Canada. The results are based on textual analysis (topic modeling) of the contributions and novelty claims in the corpus of research articles by the NRC group crafting the concept and potential applications of SWGs in the photonics domain. Topic modeling is a type of statistical modeling that uses unsupervised machine learning to identify clusters or groups of similar words within a body of text. It uses semantic structures in texts to understand unstructured data without predefined tags or training data. Adopting topic modeling as a semantic technology allows identifying two of the key non-human factors or actants: a) photonics design and simulations, and b) the fabrication techniques and facilities used to produce the physical prototypes of the photonics devices incorporating the invented SWG waveguiding effect. Using topic modeling as a semantic technology in ANT-inspired research studies focusing on non-human actants provides significant opportunities for future research.

Keywords: Actor-network theory; ANT; scientific invention; topic modeling; semantic technology; simulation tools; fabrication techniques; non-human actants; entanglement between human and non-human actors

1. Introduction

Actor-network theory (ANT) represents a research paradigm that has already been applied to science and technology studies and innovation management research by explicitly considering the contingency of the transition from invention to innovation, i.e., the adoption of an invention leading to a new practice within a community [1]. ANT's unique ontology of second-degree objectivity is based on the symmetry between human and non-human agents which allows accounting for the inherent contingency of real-life innovations [2–4]. Taking an ANT approach to the study of inventions that are emerging with a potential to be adopted in a real-life context may provide new insights into how human and non-human actors (researchers, businesses, non-human actants such as patents, design tools, or fabrication equipment) negotiate the shaping and the adoption of an emerging invention [5]. The focus on the influential role of non-human actants is particularly relevant because of its unique explanatory potential. In ANT, the terms 'actor' and 'actant' are often used interchangeably, but they have nuanced differences that are important to understand. Both terms refer to entities that can act within forming or emerging networks. 'Actor' is used in a more general sense to denote any participant with agency, while 'actant' is a more specific term borrowed from

semiotics to describe any entity, regardless of its nature, that could be granted activity by others in contributing to actions within a forming network. The distinction goes beyond traditional distinctions between human and non-human actors by treating all participants as equally significant in shaping social realities [6].

The present study focuses on a case where there is a clear separation between the invention and adoption phases of an invention – the invention of Sub-Wavelength Grating (SWG) photonic metamaterials by members of the Silicon Photonics Research Group in the Advanced Electronics and Photonics Research Centre at the National Research Council (NRC) of Canada. The invention of the SWG metamaterials was orchestrated by one of the group members who is a Principal Research Officer (PRO) at NRC (in this study we will be referring to him as the PRO). The invention was communicated and demonstrated by multiple publications and the filing of two patents in the period between 2006 (the first publication claiming the use of SWGs as a metamaterial [7]) and 2018 when the PRO received the NRC 2018 Excellence in Research Award and co-authored a review article in *Nature* – the foremost international scientific journal in the world [8]. The PRO was recognized as the lead inventor of a new type of optical waveguide mechanism based on the application SWGs [US patent 7,376,308 B2, 2008 and US patent 8,503,839 B2, 2013]. The photonic metamaterial is engineered by a unique one-step lithography approach which allows the synthesis of a new meta-material – a material that does not exist in nature but has properties that are highly beneficial for the design and fabrication of advanced microphotonic and nanophotonic devices. The PRO and his colleagues demonstrated the implementation of the new optical waveguide principle in multiple devices such as fibre-chip couplers, crossings, multiplexers, ultra-fast optical switches, athermal waveguides, sensors, polarization rotators, transceiver hybrids, and ultra-broadband interference couplers. The impact of this invention has been widely recognized and subwavelength structures are now considered key building blocks for the next generation of integrated photonic circuits. For example, the subwavelength coupler has been adopted for volume optoelectronic chip manufacturing by industry players such as IBM (U.S.A.), Global Foundries (U.S.A.), and CEA-Leti (France).

The study distinguishes between the traditional explanatory (descriptive) way of applying ANT to examine how a specific invention has actually happened, and a more proactive (anticipatory) way of applying ANT to the identification of the future actors and actants that may affect the ultimate adoption of the invention [5].¹ The research questions are as follows:

- Who were the key actors and how did the SWG photonic metamaterial research group form?
- Can topic modeling of the contributions and novelty claims articulated in the published research articles help in identifying some of the key non-human actants in the invention of the SWG photonic metamaterials?
- How did the entanglement between human and non-human actors affect the course of action of the invention?

2. Materials and Methods

2.1. Summary of Key Insights from Literature on Actor-Network Theory

ANT is a research paradigm calling for a mixed-method approach to data collection and analysis that includes as many types of accessible data sources as possible and can combine interviews, published textual data, observations, and quantitative statistics. Sieklicki and Tanev [5] identified two major ways of applying ANT to emerging innovation problems: descriptive (or explanatory) vs anticipatory. Thus, researchers should select a specific ANT approach (explanatory vs anticipatory)

¹ The results of this study were part of the Master Thesis of Samantha Sieklicki (co-author): "Using Actor-Network Theory to Examine the Invention-to-Innovation Transition of SWG Photonic Meta-Materials." Master of Applied Science Thesis, Engineering, Technology Innovation Management, 2024, Carleton University, Ottawa, ON, Canada: DOI: <https://doi.org/10.22215/etd/2024-15963>.

depending on the context of their specific research case. In the anticipatory case, the researcher moves from an observer describing the course of past action, to an examiner of the potential actors (or even participants) in the ongoing course of action [9]. Actors are always being shaped by their surrounding connections and the network is constantly being destabilized and reshaped by the actors acting in it [4]. ANT actors can be humans, non-human objects, or complex non-human actants such as culture and technology. The actor is a subject/object hybrid with the agency to act but also controlled by its relationships with other actors [10]. Limiting actors to humans destroys the symmetry between humans and non-human agents by failing to consider how humans are transformed by the agency of their physical, legal, and cultural surroundings. Selecting actors based on whether they are a source of agency (actants) preserves the focus on action, transformation, and novelty which fits very well in the context of emerging innovations [11].

Latour [4] emphasizes that ANT departs from the traditional understanding of the processes of formation of groups that always precede them [12]. Groups must be constantly maintained, renovated, or rebuilt, otherwise they cease to exist. ANT's approach to the dynamics and unpredictability of group formation and agency could be described by its commitment to address several uncertainties related to: a) the need to explore actors' agencies within a collective; b) the need to understand the nature of actors' actions (an actor is what is made to act by others; an actor 'is not the source of an action but the moving target of a vast array of entities swarming toward it' [4, p. 46]); c) the need to inquire about the agency of objects (non-human entities can no longer be considered neutral intermediaries but must be understood as silent mediators which modify the relationship among other agents); d) agencies should not be presented as matters of fact but as matters of concern focusing on making their mode of fabrication and stabilizing mechanisms visible.

Mediation refers to the co-operative work between different actors and actants. It implies that non-humans can participate in developing mediations and producing different assemblages, actions and effects. Different artifacts and technologies can develop various forms of mediation which can transform, translate, distort or modify the meanings or agents and elements [4], p. 39.

The entanglement or synergy between human and non-human actors is of special interest for ANT and has been specifically addressed in the literature. For example, Tchalakov suggested introducing the concept of "coupling" to describe the synergy in the inter-action processes occurring in scientific experiments and laboratory life. He considered the emerging relations between researchers and the actant objects they are studying as "heterogeneous couples" [13]. In the context of ANT, coupling can be defined as a process by which scientists gradually emerge as "spokesmen" for the nonhuman agents they are studying, their messengers to the rest of the audience. In essence, heterogeneous couples can be seen as the "constituent elements" of the laboratory. They could be also seen as elementary "micro-communities" which should be sometimes considered beyond the relationships between the scientists and the specific nonhuman agents they are examining. The main question here is about what supports and what stabilizes such couples because some of the actors may not (or may not be able to) speak thus concealing essential layers of what is happening in the inner life of the micro-community. Getting deep into the nature of a heterogeneous couple often means breaking standing relations with other humans and a disintegration of previously stabilized social entities. One of the key messages of Tchalakov's heterogeneous coupling theory is that the quality and intensity of the coupling between human and non-human actors affect the translation outcomes.

An additional important development of ANT that could be highly relevant for the present study is accounting for the role of the personal factor in breaking the symmetry between human and non-human actors [6,14]. The concept of 'asymmetry' that was introduced by Kapriev & Tchalakov (2009) does not assume the pre-existence of a privileged and ontologized subject of action. The reason for introducing such asymmetry is the fact that in every practical situation, there is someone or something that is the first to initiate a change and, by being first, this someone or something is in a stronger position to predefine the specific situational dynamics of any consequent translation. Latour himself insists that 'ANT is not [...] establishment of some absurd "symmetry between humans and

non-humans''' . He explains that 'To be symmetric, for us, simply means not to impose a priori some spurious asymmetry among human intentional action and a material world of causal relations' [4, p. 76]. The important point for Kapriev and Tchalakov [14] is that the suggested asymmetry is equally applicable to both human and non-human agents. Another dimension of the asymmetry arises from the importance of the personal factor in distinguishing between different actors, without ascribing an unconditional priority to the human actor as a Cartesian subject. This aspect of the asymmetry is based on the personal uniqueness and specificity of the activities which may affect the way a specific change will be actualized.

In summary, some of the key aspects of ANT which help to better investigate the emergence of science and technology inventions could be summarized as follows [12]:

- human and non-human associations are enacted in practice;
- 'following the actors' helps to better understand the social as a movement of re-association and reassembling of human and non-human elements;
- material conditions matter, and non-human elements can be agents that come into existence in association with other human and non-human agents;
- non-humans mediate human and non-human interactions;
- actants are not equal and their agential uniqueness and specificity may affect the way changes or translation happen.

2.2. Research Method

2.2.1. Research Design

This study summarizes the outcomes of a research project driven by a Principal Research Officer (PRO) from the Advanced Electronics and Photonics Research Institute at the National Research Council (NRC) of Canada. The project consisted of the conceptual development and practical validation of a new optical waveguiding principle through the engineering of a new type of photonic metamaterial (a material that cannot be found in nature but only developed by engineering the composition and the geometry of specific nanophotonic structures). The research project has a well-defined duration from 2006 (first publication) to 2018 (publication of a review article in Nature which is formal evidence of the achievement of the inventors). The year 2018 marks the formal existence of an invention and the potential beginning of its adoption phase. Delimiting the research study period to 2018 is part of the methodological setup which requires a specific end of the study period. However, the 2018 end of the study period should not lead to the misleading impression that research on SWG photonic metamaterials has been completed. A recent review paper by the NRC research group [15] demonstrates that the field has grown significantly stronger since 2018. In addition, the group has recently discovered a new type of metamaterial waveguide, known as Huygens waveguide [16].

The research method adopts the ANT perspective by examining the contingency and unpredictability of the engagement of different actors, the role of the non-human actors, and the entanglement between human and non-human actors in explaining the ultimate success of the invention. The study focuses on examining published academic journal articles. In ANT, scientific publications play a crucial role as they are considered actants within the network of scientific knowledge production. Publications are seen as actants that can influence the direction of research, shape scientific debates, and impact funding decisions. They contribute to the stabilization of networks by documenting and legitimizing scientific claims. At the same time, examining the temporal development of claims may help in following unexpected changes and new developments. Publications help transform complex scientific ideas into accessible formats that can be understood and utilized by various stakeholders, including policymakers, businesses, practitioners, and the general public [17]. We found 22 articles in the period between 2006 and 2018 that included the PRO as a co-author and discussed different aspects or applications of SWG photonic metamaterials. The analysis of the articles focused on two key aspects – authorship and novelty/contribution claims. We

have also had multiple Q&A sessions with the PRO and semi-structured interviews (with follow-up Q&As) with two domain experts who were indirectly involved in the invention.

2.2.1. A Topic Modeling Approach to Examining Novelty and Contribution Claims in Research Articles

The analysis of the content of the research articles was based on performing a topic modeling analysis [18,19] on a corpus of 104 extracted paragraphs that were identified as novelty claims and research contributions. Each paragraph was considered as an individual text document. We have used the text analytics capabilities of Orange Data Mining software (<https://orangedatamining.com/>) and adopted the most popular topic modeling algorithm – LDA [18]. The logic of LDA could be summarized as follows: i) it assumes that there are k topics across all of the documents; ii) it distributes these k topics across document m by assigning each word a topic; iii) for each word w in document m, it assumes its topic is wrong but every other word has been assigned the correct topic; iv) probabilistically assigns word w a topic based on two criteria – what topics are in document m, and how many times the word w has been assigned a particular topic across all of the documents; v) it repeats this process multiple times to reach a stable distribution of both topics in documents and words in topics.

The LDA algorithm considers every text document (paragraph) as a mixture of topics, and every topic as a mixture of words. Words can be shared between topics and the topics can be shared among documents. LDA identifies combinations of words that are semantically interrelated and tend to appear together across different documents. The combinations of words help the identification of specific themes that are latently present in the corpus. In addition, LDA organizes the corpus by clustering the documents corresponding to each topic. The paragraphs clustered in each topic are ranked in terms of the degree of their association with it. A closer examination of the topical organization of the paragraphs enables the interpretation of the overall theme and the labeling of the topics [20].

3. Results

3.1. Examining the Authorship of Scientific Publications

We have adopted the ANT research philosophy to examine the authorship of the 22 articles. The analysis answers the first research question: Who are the key actors and how did the SWG photonic metamaterial research group form? Table 1 provides a visual representation of the involvement of different authors during the study period between 2006 and 2018. The first author (P. Cheben) is the PRO and is part of all 22 publications. The letters in the cells below each year of publications indicate the country of origin of the co-authors.

A closer examination of Table 1 leads to several interesting findings that demonstrate the need to adopt the ANT research perspective. These findings could be summarized as follows.

Table 1. A visual illustration of the contribution of different authors to the 22 articles published between 2006 and 20018. The table shows the countries of origin of the authors as well as their participation as co-authors in different years of publication.

N	Author	Country	2006	2007	2010	2011	2012	2014	2015	2016	2017	2018
1	Cheben	Canada	C	C	C	C	C	C	C	C	C	C
2	Janz	Canada	C	C	C	C			C			
3	Xu	Canada	C	C	C		C	C	C	C		
4	Densmore	Canada	C		C		C					
5	Schmid	Canada		C	C	C	C	C	C	C	C	C
6	Lapointe	Canada		C	C	C	C		C			

7	Post	Canada	C								
8	Bock	Canada	C	C	C			C			
9	Delage & Hall	Canada	C		C						
10	Lamontagne	Canada	C					C			
11	Glesk	UK									
	Halir, Molina-Fernandes, & Ortega-Monux	Spain				SP	SP	SP	SP	SP	SP
13	Wangue-mert-Perez	Spain				SP	SP	SP	SP		SP
14	Aers & Maese-Novo	Canada & Spain			C & SP						
15	Alonso-Ramos	Spain				SP	SP	SP		SP	
16	Perez-Galacho	Spain				SP				SP	
17	Xiong & Ye	Canada				C					
18	Wang	Canada						C	C	C	
19	Dado	Slovakia						SL		SL	SL
20	Benedikovic & Vachon	Slovakia & Canada						SL		SL	
21	Painchaud & Picard	Canada						C			
22	Khokhar et al.	4 UK & 2 Spain						UK & SP	UK & SP	UK & SP	
23	Duran-Valdeiglesias et al.	3 Spain & 1 France						SP & FR			
24	Baudot et al.	7 France, 4 Can, 1 Spain, & 1 USA							FR, C, SP & US		
25	Atwater et al.	4 UK, 3 Czechia, 1 Can, 1 Slovakia, 1 USA								UK, CZ, C, SL & US	

- It is impossible to identify a stable group of co-authors. The composition of the group is continuously changing. The only “stable” actors appear to be the PRO and one of his colleagues

(Schmid) who succeeded in engaging the contributions of different co-authors at different times. The variety of countries of origin illustrates the diversity of contributions and actors at different times. The interviews with the two domain experts who had direct exposure to the context of the invention have indicated that one of the key stabilizing factors in pursuing the invention was the person of the PRO who was able to build on his current and pre-existing personal and institutional relationships across different countries to engage co-authors who have contributed to developing further the PRO's initial idea.

- Interestingly, the PRO mentioned that without incidentally meeting one of the domain experts interviewed as part of this study, who introduced him to the OptiFDTD simulator, the SWG coupler idea may not have been efficiently validated. The initial collaboration between the RO and the domain expert resulted in a joint publication [21]. Another interesting case is the last one (row 25). It refers to the 2018 publication in Nature which includes the co-authorship of one of the competitive groups from the USA. The PRO has invited the leaders of a competing group from another country to make a more valuable invited review article. This is just an illustration of a unique personal characteristic of the PRO – his ability to cooperate and engage others in pursuing a common valuable goal. This finding supports the point made by Kapriev and Tchalakov [20] that the unique personal characteristics of an actor could be highly influential in determining the course of action.
- There are two gaps in the years of publication – 2008/2009 and 2013. There are two ways of interpreting these publication gaps. First, as it appears, the SWG photonic nanomaterial research was not part of an initially planned and well-funded research project. In this sense, its progress was contingent on the availability of resources and negotiating the engagement of new contributors. Second, the two gaps in the publication years correspond to the filing of two patents that were directly related to the invention. The first patent was filed at the end of 2007 and granted at the beginning of 2010. It could explain the lack of publications in 2008 and 2009. The second patent was filed at the beginning of 2012 and granted in the second half of 2013. The two patents refer to two different applications of the SWG waveguiding effect. The filing of the patents demonstrates the anticipation of the future adoption of the invention. The analysis of the patent filing shows that the application of ANT in its traditional explanatory mode of inquiry could inform its application in an anticipatory mode which aims at clarifying future developments.
- A deeper analysis of specific co-authors could provide additional insights into the diversity and unexpectedness of contributions from the different countries. For example, in one of the Q&A sessions the PRO mentioned that if PhD student Bock (row 8 in Table 1) had not been involved at that specific time, the research project would not have developed the way it did. At that time it was mostly him and his colleague Schmid driving the research activities and the involvement of collaborators and PhD students from Spain (“the Spaniards”), the project would never have reached its culmination in 2018. Interestingly, the Spaniards are the second largest group of co-authors after the Canadians. It is not an accident that the PRO completed his PhD in Spain and spent years of professional research work there. He maintained valuable working relationships with his former colleagues which allowed him to seek cooperation with younger researchers who were eager to make a difference in the newly emerging SWG domain of research.

3.2. Topic Modeling of Novelty and Contribution Claims

We have explored different numbers of topics that could describe the 104 claims in the 22 articles. Each topic comes with 10 of the most frequent words that characterize the paragraphs associated with it. Below we show the results (the most frequent words and the number of claims associated at least 60% with the most frequent words for a given topic) of three different topic models including 5, 4, and 3 topics. The topics are labelled in a way that could distinguish between different topic models and different topics within a specific topic model. For example, Topic 5T2 refers to the second topic

in the 5 topic model. The text in the brackets after each topic label suggests a brief interpretation of its content.

3.2.1. A topic Model Including 5 Topics

- Topic 5T1 (*photronics design/simulation tools and techniques*): photonic, FDTD calculations, calculations, FDTD, operation, metamaterial, simulations, advantage, microphotonic (18 claims)
- Topic 5T2 (*photonic metamaterial properties*): microphotonic, novel, compact, metamaterials, procedure, transmission, material, photonic, simulation, implement (16 claims)
- Topic 5T3 (*SWG metamaterial applications*): SWGs, operation, photonic, compact, superior, unique, metamaterial, advantage, applications, impact (18 claims)
- Topic 5T4 (*novel photonic devices and structures*): photonic, operation, simulation, SWGs, Mach, Zehnder, Mach Zehnder, novel, structure, all-optical (22 claims)
- Topic 5T5 (*fabrication equipment, techniques and capabilities*): structure, remarkably, UV lithography, UV, simulations, lithography, composite, material, compact, ultraviolet UV lithography (22 claims)

3.2.2. A topic Model Including 4 Topics

- Topic 4T1 (*photronics design/simulation tools and techniques; fabrication equipment, techniques and capabilities*): photonic, simulations, FDTD calculations, calculations, FDTD, operation, lithography, metamaterial, UV, UV lithography (21 claims)
- Topic 4T2 (*photonic metamaterial properties*): compact, structure, novel, microphotonic, metamaterials, material, procedure, compact structure, transmission, applications (23 claims)
- Topic 4T3 (*unique advantages of photonic metamaterials*): operation, photonic, remarkably, structure, metamaterial, unique, superior, compact, advantage, impact (23 claims)
- Topic 4T4 (*SWG metamaterial applications*): photonic, SWGs, operation, Zehnder, Mach, Mach Zehnder, simulation, material, novel, all-optical (29 claims)

3.3.3. A Topic Model Including 3 Topics

- Topic 3T1 (*photronics design/simulation tools and techniques; fabrication equipment, techniques and capabilities*): simulations, simulation, photonic, lithography, UV, UV lithography, metamaterial, unprecedented, FDTD calculations, calculations (32 claims)
- Topic 3T2 (*novel photonic metamaterial applications*): photonic, compact, novel, structure, material, microphotonic, Zehnder, Mach Zehnder, Mach, applications (33 claims)
- Topic 3T3 (*unique properties of SWG metamaterials*): operation, SWGs, photonic, remarkably, lithography, unique, superior, compact, metamaterial, structure (31 claims)

The results for the three topic models above show a consistency of the themes across the different topic models and a relative stability of the emerging themes. What is most interesting is that the three topic models explicitly identify two major non-human actors that have substantially influenced the invention: a) photonics design/simulation tools and techniques (simulations, FDTD calculations, FDTD, calculations), and b) the fabrication equipment, techniques and capabilities (lithography, UV lithography, composite material) used to produce the physical prototypes of the photonics devices incorporating the invented SWG waveguiding effect. The 5 topic model includes these two actors as separate topics. The 4 and 3 topic models merge them. They are, however, distinctive enough to be considered equally important, and fundamentally necessary factors that have enabled the emergence of the invention. What is most interesting here is that photonics design/simulations and experimental fabrication techniques are key elements of the experimental configurations used to demonstrate the concept, the operation, and the application of the initial invention. Photonics design and simulations provide a basis for running virtual experiments, while the fabrication equipment is key for prototyping and proof of concept. Simulations are the starting point that prepares real physical prototyping and validation. That is why the first publications focus on simulations while the later

ones include the fabrication of physical prototypes and testing. The analysis below will focus on the results of the 3 topic model.

3.3. Examining the Novelty/Contribution Claims Associated with the 3 Topic Model

Topic 3T1 refers to two major non-human actants in the invention process – photonics simulation tools and fabrication methods and techniques. This is an impressive result since it suggests that topic modeling can play the role of semantic technology that could help in structuring authors’ novelty claims in a way that identifies two of the major non-human actants from an ANT point of view. It provides a partial answer to the second research question: What was the role of non-human actors in the invention of the SWG photonic metamaterials? It should be emphasized that these are not the only non-human actors in this research. As an example of another non-human actor one could mention the networking infrastructure of the photonics community in Ottawa, Ontario, which has significantly enhanced the advanced adoption of the design and simulation tools by the PRO and the NRC silicon photonics research group. This finding shows the potential of combining the ANT research approach with text analytics tools as semantic technologies providing valuable insights relevant to the study of scientific inventions.

Topic 3T2 refers to novel applications based on the implementation of SWG metamaterials. Topic 3T3 refers to unique and remarkable principle of operation of SWG metamaterials. Tables 2, 3 and 4 below show examples of textual paragraphs that are most highly associated with the three topics.

Table 2. Topic 3T1 textual examples referring to photonics simulation and fabrication methods: simulations, simulation, photonic, lithography, UV, UV lithography, metamaterial, unprecedented, FDTD calculations, calculations.

Degree of association	Claims associated with Topic 1
0.982	An obvious practical advantage of our fabrication method is that AR facets can be produced by using standard lithographic and etching techniques at the wafer level.
0.982	We reported results of numerical simulations of reflection and transmission spectral filters based on Bragg gratings in subwavelength grating metamaterial waveguides. We demonstrated that filters with spectral bandwidths as small as a few tens of picometers can be implemented in silicon waveguides while keeping minimum structural dimensions compatible with deep-UV lithography (>100 nm).
0.969	We have shown both numerically and experimentally that substrate leakage losses in SWG waveguides are related directly to the effective index (or, equivalently, group index), and that this relation is invariant on the specifics of SWG geometry. This finding allows the designer to treat SWG structures abstracting from the BOX thickness constraint, and readily estimate the leakage losses from the calculated effective index using the results.
0.965	We demonstrate the potential of SWG refractive index engineering through the realization of practical functional components. ... The coupler principle is based on a gradual modification of the waveguide core refractive index and the corresponding mode size transformation by changing the volume fractions of the Si and SU-8 materials that form the composite waveguide core.
0.958	We have shown, for the first time, that the efficient and widely used CMT formalism can be advantageously applied to Bragg gratings in SWG metamaterial waveguides, providing the coupling coefficients are determined by rigorous 3D tools such as FMM.

0.957	In this Letter, for the first time, to the best of our knowledge, we report on the experimental demonstration of an ultra-directional fiber-chip grating coupler seamlessly fabricated by using 193 nm deep-ultraviolet (deep-UV) optical lithography, a viable tool for large-volume production.
0.904	By exploiting the principle of SWG refractive index engineering in planar waveguides, the coupler was fabricated using a single-etch step process and backside metal deposition.
0.830	We used 3D finite-difference time-domain simulations to minimize loss, crosstalk and polarization dependence.
0.826	We demonstrate the proposed coupling principle on examples of various two-dimensional coupling structures using 2D Finite Difference Time Domain (FDTD) calculations
0.825	We demonstrate the proposed principle by two-dimensional Finite Difference Time Domain (FDTD) calculations of various SWG structures designed for the silicon-on-insulator (SOI) platform
0.664	We demonstrate the use of subwavelength gratings etched into the facets of silicon-on-insulator ridge waveguides as a means of reducing facet reflectivity by the gradient-index effect.

Table 3. Topic 3T2 textual examples referring to novel photonics device applications: photonic, compact, novel, structure, material, microphotonic, Zehnder, Mach Zehnder, Mach, applications.

Degree of association	Claims associated with Topic 2
0.976	We report on the experimental demonstration of ultrafast all optical switching and wavelength down-conversion based on a novel nonlinear Mach-Zehnder interferometer with subwavelength grating and wire waveguides. Unlike other periodic waveguides such as line-defects in a 2D photonic crystal lattice, a subwavelength grating waveguide confines the light as a conventional index-guided structure and does not exhibit optically resonant behaviour. Since the device had no dedicated port to input optical signal to control switching a new approach was also implemented for all optical switching control.
0.976	Our subwavelength grating waveguide is unique in that the structure supports a true lossless mode. By modifying the pitch, width and duty cycle of the subwavelength grating, the effective index of the medium can be engineered locally. This technique provides a means to tailor the effective index, mode profile and dispersion of the subwavelength grating waveguide.
0.975	We demonstrated refractive index engineering in a microphotonic waveguide using SWGs, including implementations in practical components at telecom wavelengths. Our technique circumvents an important limitation in integrated optics, that is, the fixed value of the refractive indices of the constituent materials.
0.973	We introduced a new concept of refractive index engineering in optical waveguides. The waveguide is longitudinally patterned with a subwavelength grating (SWG), consisting of segments of a high-refractive-index core material interlaced with a lower refractive-index cladding material. Since the refractive-index contrast can be changed by simply controlling the grating period, waveguides with different optical parameters can be realized on the same chip.
0.973	In this paper, a new waveguide principle based on the formation of a subwavelength grating (SWG) in a waveguide core is proposed and

	demonstrated experimentally. In contrast to waveguides based on line-defects in 2D photonic crystal lattices, the light is confined in a SWG waveguide core covered with a cladding material of a lower refractive index, as in conventional index-guided structures. The core is a composite medium formed by periodically interlacing silicon segments with a material of a lower refractive index at the subwavelength scale.
0.964	Fundamental to the excellent performance of our coupler is also an original design of the coupler tip near the chip edge, facing the optical fiber. This design procedure, reported here for the first time, is critical to obtain high coupling efficiency, as are the effective medium synthesis procedure and the quantitative understanding of the effect of coupling to substrate, both presented here for the first time.
0.958	An important novelty in this design is compensation of the index mismatch and loss at the junction between two coupler sections with different grating geometries, i.e., the segmented section and the section with the gaps partially filled with narrow silicon segments.
0.958	In this paper to the best of our knowledge we demonstrate for the first time a practical realization of a novel ultra-fast all-optical interferometric sampling/switching device based on photonic nanowire and subwavelength grating waveguides placed in the Mach-Zehnder geometry capable of all-optical picosecond sampling and switching.
0.958	We experimentally demonstrated and analysed a novel ultrafast all-optical nonlinear Mach-Zehnder interferometric switching device, the MZIS which is based on the combination of subwavelength grating waveguide and wire waveguide. The device is capable of performing all-optical picosecond switching.
0.958	In this review we discuss how bringing metamaterials into optical waveguide technologies and on-chip architectures provides new degrees of freedom to control the flow of light in integrated photonic devices.
0.958	In summary, we have proposed and investigated a novel method to achieve a compact and fabrication tolerant polarization splitter and rotator (PSR) using a subwavelength grating (SWG) structure. The PSR comprises a silicon wire waveguide coupled to a SWG waveguide. The fabrication tolerance is improved by engineering the equivalent refractive index of the SWG waveguide.
0.948	This compact SWG structure is among the smallest yet efficient couplers reported, and further reduction in length appears feasible.
0.948	We propose a novel method to implement a compact and fabrication-tolerant polarization splitter and rotator (PSR) on the silicon-on-insulator platform. The PSR consists of a silicon wire waveguide coupled to a subwavelength grating (SWG) waveguide in an asymmetrical directional coupler.
0.904	By exploiting the dispersive properties of sub-wavelength gratings for the first time, we have designed a directional coupler that exhibits a fivefold bandwidth enhancement compared to conventional directional couplers. Our approach yields a compact device and does not deteriorate the coupler's phase response.
0.903	We report on the experimental demonstration and analysis of a new waveguide principle using subwavelength gratings. Unlike other periodic waveguides such as line-defects in a 2D photonic crystal lattice, a subwavelength grating waveguide confines the light as a conventional index-guided structure and does not exhibit optically resonant behaviour.

0.901	In conclusion, we have demonstrated that a remarkably efficient AR effect is exhibited by monolithic GRIN SWG structures on SOI ridge waveguide facets, fabricated using standard patterning and etching techniques at the wafer scale.
0.897	To our knowledge, this is the highest efficiency with minimal wavelength and polarization dependence yet reported for a microphotonic coupler. Furthermore, the SWG coupler exhibits a high tolerance to the feature size variations that may arise from limited accuracy of lithography and etching.

Table 4. Topic 3T3 textual examples referring to the principles of operation of SWG photonic metamaterials: operation, SWGs, photonic, remarkably, lithography, unique, superior, compact, metamaterial, structure.

Degree of association	Claim associated with Topic 3
0.983	SWG sensing waveguides exhibit two advantages that are of great practical interest. First, it is clear that these sensitivities can be achieved for a wide range of silicon thicknesses (220–300 nm). This affords a significant design flexibility, especially compared to TM sensing waveguides that operate with silicon thicknesses of at least 250 nm. Second, propagation losses in SWG waveguides have been experimentally shown to be of the order of only 2 dB/cm. Thus these waveguides may achieve substantially longer interaction length than slot waveguides that exhibit losses of 8–10 dB/cm.
0.983	We developed a new technique for implementing the all-optical switching control of the MZIS. ... Note that one MZIS arm is a wire waveguide and the second is a SWG waveguide.
0.978	Here, we leverage the inherent anisotropy and dispersion of a sub-wavelength structured photonic metamaterial to demonstrate ultra-broadband integrated beam splitting. Our device, which is three times more compact than its conventional counterpart, can achieve high performance operation over an unprecedented 500 nm design bandwidth exceeding all optical communication bands combined, and making it one of the most broadband silicon photonics components reported to date.
0.964	Compared to SOI couplers with shallow etch grating region, the present approach has two important practical benefits: i) both grating coupler and interconnecting waveguide are defined in a single-etch step down to the depth of the BOX layer and ii) the SWG structure allows to control the coupling strength and apodize the grating profile.
0.958	We show for the first time that SWG waveguides can be utilized to engineer the dimensional dependence of the waveguide mode effective index. We use the unique property of SWGs to implement a polarization splitter and rotator with a substantially enhanced tolerance to waveguide size variations resulting from fabrication.
0.958	The benefit of using the SWG to engineer the mode profile for sensing include the mode delocalization effect and providing the analyte to reach the modal field in the gaps of the SWG structure. More than 25% of the field power is concentrated in the sensing part of the SWG waveguide (superstrate and gaps), compared to less than 7% in a slab waveguide (only the superstrate is sensing). This explains the sixfold enhancement in the bulk and surface sensitivities, as indicated by our results.
0.948	In this paper we present design solutions that eliminate these sources of loss and demonstrate that SWG couplers can outperform inverse taper couplers in terms of both coupling loss and polarization dependent loss.

0.948	Here we present the use of SWGs for facet reflectivity reduction by the gradient-index (GRIN) effect. We use SWGs with triangular teeth, etched into the facet from the top.
0.946	In this work, we demonstrate for the first time the realization of an ultra-directional L-shaped grating coupler, seamlessly fabricated by using 193-nm deep-ultraviolet (deep-UV) lithography. We also include a subwavelength index engineered waveguide-to-grating transition that provides an eight-fold reduction of the grating reflectivity,
0.933	In this Letter, we propose a new grating coupler concept which achieves for the first time, to the best of our knowledge, both broadband operation bandwidth and high coupling efficiency, simultaneously. The coupler operation principle is based on the use of the zero diffraction order, instead of the first order that is typically employed in conventional surface grating couplers. In this specific (zero-order) regime, the radiation angle variation with wavelength is minimized, hence substantially broadening the coupler bandwidth.
0.932	The coupler exploits the principle of subwavelength refractive index engineering which mitigates loss and wavelength resonances by suppressing diffraction effects. The proposed technique allows precise control of the modal field at the coupler tip to optimize coupling efficiency between the optical fiber and the silicon chip, for both TE and TM polarizations simultaneously, which helps minimizing the polarization dependence.
0.931	In this paper, we propose a new approach which, building upon these techniques, exploits the unique advantage of dispersion properties of SWG waveguides. For the first time, a Bragg grating comprising SWG metamaterial waveguide core loaded with lateral segments is proposed and analyzed.
0.831	Here we use, for the first time, the dispersive properties of sub-wavelength gratings to achieve a fivefold enhancement in the operation bandwidth of a silicon-on-insulator directional coupler. This approach does not compromise the size or the phase response of the device.
0.664	We have demonstrated a set of suspended MIR silicon SWG engineered devices.
0.661	Here, we propose a new type of sensing waveguide based on subwavelength gratings (SWGs).
0.661	Here we propose, for the first time, the use of sub-wavelength gratings (SWGs) to design broadband directional couplers.
0.647	An important advantage of our SWG structures is that they can be fabricated with a single etch step.

3.4. Entanglement Between Human and Non-Human Actors

The identification of the two non-human actors (photonics design/simulations and fabrication equipment/techniques) allows us to discuss the effect of the entanglement between human and non-human actors. Before doing that, we should point out that this topic requires a more detailed discussion that would go beyond the scope of this article. However, we could mention that the employment of the two non-human actors above required solid professional expertise acquired over many decades. At the same time, the personal predisposition of researchers plays a key role. The interviews with our two respondents have shown that the PRO has been highly proficient in mastering design and simulation tools as well as in linking his deep knowledge of theoretical electromagnetics and optics to the design context of photonics simulation tools. The PRO benefited from the proximity to a local photonics design automation company to adopt their commercial FDTD simulation tool and did not hesitate to shift to an alternative provider when the logic of the simulation required them to do so. In addition, the microphotonics fabrication facilities at NRC are unique in

Canada and this part of North America. The Advanced Electronics and Photonics Research Centre has been hosting the Canadian Photonics Fabrication Centre which owns top fabrication facilities and empowers the human resources that were able to meet the challenge and fabricate the SWG photonic metamaterial prototypes. In this sense, the empirical observations are in line with previous ANT research which suggests that the quality of the entanglement between human and non-human actors affects the quality of the translation outcomes (see third research question above).

4. Conclusion

The article adopts the ANT perspective by focusing, first, on examining the authorship of research articles and, second, on applying topic modeling as a semantic technology to examine the contributions and novelty claims in 22 research articles published between 2006 and 2018. The study provides answers to all three research questions and demonstrates the potential of combining the ANT approach with text analytics techniques as semantic technologies enabling the study of the role of the non-human actors in scientific invention processes.

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