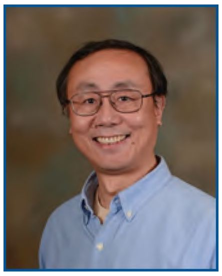
DAWN OF CAVITY SPINTRONICS

BY CAN-MING HU



Can-Ming Hu <hu@physics.umanitoba.ca>, Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2

HEROES OF SPINTRONICS

Heroes are not always stars. This we know from the movies, but it is also true in the community of physicists. In the field of spintronics, my heros are Robert Silsbee and Mark Johnson. In 1979, Robert H. Silsbee, the 50-year old Cornell University professor on his sabbatical leave at the University of Paris-Sud, published an article in Physics Review B with the title "*Coupling between ferromagnetic and conduction-spin-resonance modes at a ferromagnetic-normal-metal interface*" [1]. It revealed two new physical characteristics of a spin current. (1) through the micro-wave excitation of ferromagnetic resonance (FMR), a spin current can be generated in a ferromagnetic metal, which will flow into an adjacent normal metal. (2) Such a spin current pumped by FMR impacts the spin dynamics in the metal via the exchange interaction. Several decades later, from these two effects came Spin Pumping [2] and Spin Torque [3], two seminal concepts of contemporary magnetism. Today, every conference on spintronics has celebrated talks on spin pumping. However, Silsbee *et al.*'s ground breaking paper has only been cited about 100 times in four decades. Many students of today studying spin pumping have never read that paper, and some have never even heard of it. The same thing has happened in the history of cinematography. In an era when movie goers celebrate blockbusters like "*Star Wars*", few of us remember the epic "*2001, A Space Odyssey*", a ground breaking work of art produced by Stanley Kubric in 1968, which enlightened George Lucas.

Kubric directed only 16 movies in his life time. He was too meticulous to endure anything but a masterpiece. So was Silsbee, who published only 82 papers. His 1979 paper on spin pumping [1] demonstrated optical injection and detection of spin current. That work inspired Silsbee's vision of electrical spin injection and detection, in which a spin current would be generated by a battery and detected by an electrometer. Twenty years later, that vision became the main theme of spintronics [4]. But by then, it was a bold idea. The giant magneto resistance effect (awarded the 2007 Nobel Prize) would be discovered nine years later [5], and the word "spintronics" did not exist. So in 1980, when Silsbee led his PhD student Mark Johnson to explore electrical spin injection into metals, it was not a race. It was a courageous lonely journey into a no man's land, as research in physics can often be.

SUMMARY

An emerging field of cavity spintronics connects some of the most exciting modern physics, such as quantum information and quantum optics, with one of the oldest sciences on earth, magnetism.

Johnson's adventure in Ithaca working on spin injection was a scientific odyssey reminiscent of the epics of Homeric heroes. His achievement came after multiple years of failure. It shows that truly original work demands courage more than ideas. The best way to appreciate Johnson and Silsbee's originality and courage is to read their 1985 *PRL* paper [6] in comparison with a paper published by Jedema *et al.* in 2002 in *Nature* [7]. Silsbee predicted that spin accumulation was inversely proportional to sample volume, but in 1980, there was no clean room at Cornell University for making nano-devices. So Johnson started by developing his own lithography for making small samples. The next challenge was in the measurement. Even in the smallest sample he made for spin injection (where all three dimensions are the order of 100 µm), the signal was only a few picovolts. To measure it, Johnson designed a special bridge circuit, and used it together with a SQUID voltmeter and a lock-in to beat down noise. The third major obstacle was the spurious magnetoresistance effect in his device, which hampered his progress for years until he invented (together with Andras Janossy) the non-local detection method which measured spin diffusion instead of sending a current directly from the injector to the detector. Finally, to conclusively verify the spin signal, he and Silsbee introduced the Hanle effect [8] from atomic physics into condensed matter physics. By using a magnetic field to control spin precession, the Hanle effect became the compass that guided his courageous adventure in spin transport [6].

Decades later, nonlocal detection combined with the Hanle effect would become the norm of performing spin injection and detection experiments. This was neatly shown in Nature's 2002 reproduction of the spin injection experiment [7]. As Silsbee predicted, by shrinking the device size from micrometers to nanometers, Johnson's picovolt spin signal detected at cryogenic condition in 1985 was enhanced by four orders of magnitude, so that in 2002 it was measured at room temperature. This shows that spintronics is a nano science. Today, with the great advancement in nanotechnologies, spin current is not only routinely measured in the labs by students, but it is commercially used in new storage devices [see the article "*STT-RAM Memory Devices*", by Arora *et al*.]. In nano-structured magnetic devices, spintronic effects are often so large, so important, and so useful, that they are transforming the old science of magnetism, and thereby innovating our information and communication technology [9]. As will be highlighted in this article, the advancement of spintronics is now merging with the development of cavity techniques used in the field of quantum physics [10–13].

STARS AND INNOVATORS IN CAVITY QUANTUM ELECTRODYNAMICS

In 2012, the Royal Swedish Academy of Science decided to award the Nobel Prize in Physics to Serge Haroche and David Wineland. They developed ingenious trap [10] and cavity [11] techniques to measure and manipulate particles in quantum states. Their techniques allow the fundamental interaction between light and matter to be studied in its most elementary form in the quantum regime. Reaching this regime has generated the field of cavity QED [12], and opened the door to a new era of using coherent quantum effects for quantum information processing [13].

Innovative condensed matter physicists are often inspired by atomic physics. In a paper published in 2004 in *Nature* [14], Schoelkopf and his team at Yale University showed how to take cavity QED from Haroche's atomic world to a solid-state system, by replacing the atoms with a superconducting qubit. Reading Schoelkopf's paper, some of us working on spintronics immediately had the idea of using a spin two-level system in magnetic materials to couple with photons in the microwave cavity. Doing so would propel the research in magnetization dynamics into a completely new regime of quantum coherent spin-photon coupling, merging spintronics with circuit QED to advance both fields. In 2010, before any experimental pioneers set their footprints on the new land, theoreticians prepared a map of quantum physics [15] for the dream world of Cavity Spintronics.

SETTLERS OF THE CAVITY SPINTRONICS

In a theoretical paper published in *PRL* [15], Michael Flatté and his student at the University of Iowa analyzed the interaction of a nanomagnet with a single photonic mode of a cavity in a fully quantum-mechanical treatment. Their result predicted an exceptionally large quantum-coherent magnon-photon coupling which reaches the strong coupling regime (which means the coupling strength exceeds the dissipation of the coupled system).

Three years later in 2013, the German group of Hans Huebl and Sebastian Goennenwein at the Walther-Meißner-Institut published in *PRL* the first experimental result on magnon-photon coupling [16]. They demonstrated how to use microwave transmission experiments to measure at 50 mK the strong coupling between magnons in a yttrium iron garnet (YIG) and microwave photons in a superconducting coplanar microwave resonator. Huebl is an expert in quantum microwave devices, and Goennenwein is a driving force of spin mechanics. Other Viking explorers arrived at the Newfoundland of cavity spintronics from very different galaxies of physics.

In the galaxy of superconducting device and quantum computing, Yasunobu Nakamura at the University of Tokyo has been a star since he published in 1999 the paper "*Coherent control of macroscopic quantum states in a single- Cooper-pair box*" in *Nature* [17]. That was the first demonstration of a practical solid-state qubit which employed the macroscopic quantum coherence. Such a superconducting qubit was what Schoelkopf later used in his circuit QED experiments. In another galaxy, Schoelkopf's young colleague Hong-Xing Tang at Yale University is a rising star of nano-electromechanical systems and quantum optics. Via the wormhole of quantum coherence, both Nakamura and Tang entered the field of cavity spintronics, setting their feet on the soil of the magnons in magnetic materials.

Both of their studies of magnon-photon coupling were published in 2014, showing how to tune the coupling strength. In Nakamura's paper [18], the Tokyo team used a variable-sample method. Their experiment was performed at cryogenic temperatures in the quantum regime where the average number of thermally or externally excited magnons and photons was less than one. The experiment of Tang's group, in contrast, was performed at room temperature. In their paper [19], the Yale team used a variable cavity method to show interesting dynamic features such as classical Rabi-like oscillations, magnetically induced transparency, and the Purcell effect. Comparing both papers, alerted readers may notice that the question arises regarding the distinction between the quantum and classical regime of magnon-photon coupling. That's the point to which we will return in the next section.

All of these pioneering works done in Germany, Japan, and the USA were performed by measuring microwave spectra of coupled magnet-cavity systems. The vision of Silsbee has taught us that the highway of spintronics is spin transport [6]. Building this highway for cavity spintronics requires developing an electrical method to detect the magnons coupled with photons. Here come the Canadian settlers.

For decades in the community of semiconductor physics, electrical detection of charge dynamics has been extensively used [20]. Since 2004, our group has set out to expand this technique to study spin dynamics in ferromagnetic metals [21,22]. By then, it was nearly a no man's land. But through a decade of effort by many spintronics groups worldwide, this branch of magnetism is now booming with diverse methods available [23]. In the paper entitled "*Spin Pumping in Electrodynamically Coupled Magnon-Photon Systems*" [24], which was published in 2015 as a *PRL* Editor's Suggestion, Lihui Bai and Michael Harder *et al*. at the University of Manitoba used the tool of spin pumping to study the magnon-photon coupling. This was achieved by designing a special microwave cavity as schematically shown in Fig. 1. This set-up enables both microwave transmission measurement of the cavity, as well as microwave photo-voltage measurements of the ferromagnet. Setting in the cavity a bilayer device of YIG/Pt fabricated by the group of John Xiao at the University of Delaware, the microwave photo-voltage measured in Pt probes the spin current generated by the FMR in YIG. This enables studying the impact of magnon-photon coupling on the spin transport [25].

Not only that, in contrast to previous studies guided by the theory of quantum strong coupling [15], the Manitoba-Delaware collaboration did not follow the quantum map. Instead, a concise theory was developed showing that the magnon-photon coupling can be described on the classical footing of electrodynamics [24]. This gives cavity spintronics an alternative classical map.

QUANTUM OR CLASSICAL PHYSICS, THIS IS THE QUESTION

Initial interest in cavity spintronics was based on a quantum perspective [15]. Via the quantum strong coupling of magnons and photons which generates entangled states of spin orientation and photon number, quantum information can be easily transferred between the light and the magnet via Rabi oscillations [25]. Such quantum entangled states require cryogenic conditions, because the interaction of magnons with phonons through spin-orbit coupling limits the dephasing time at room temperature [15]. That was one of the reasons that the

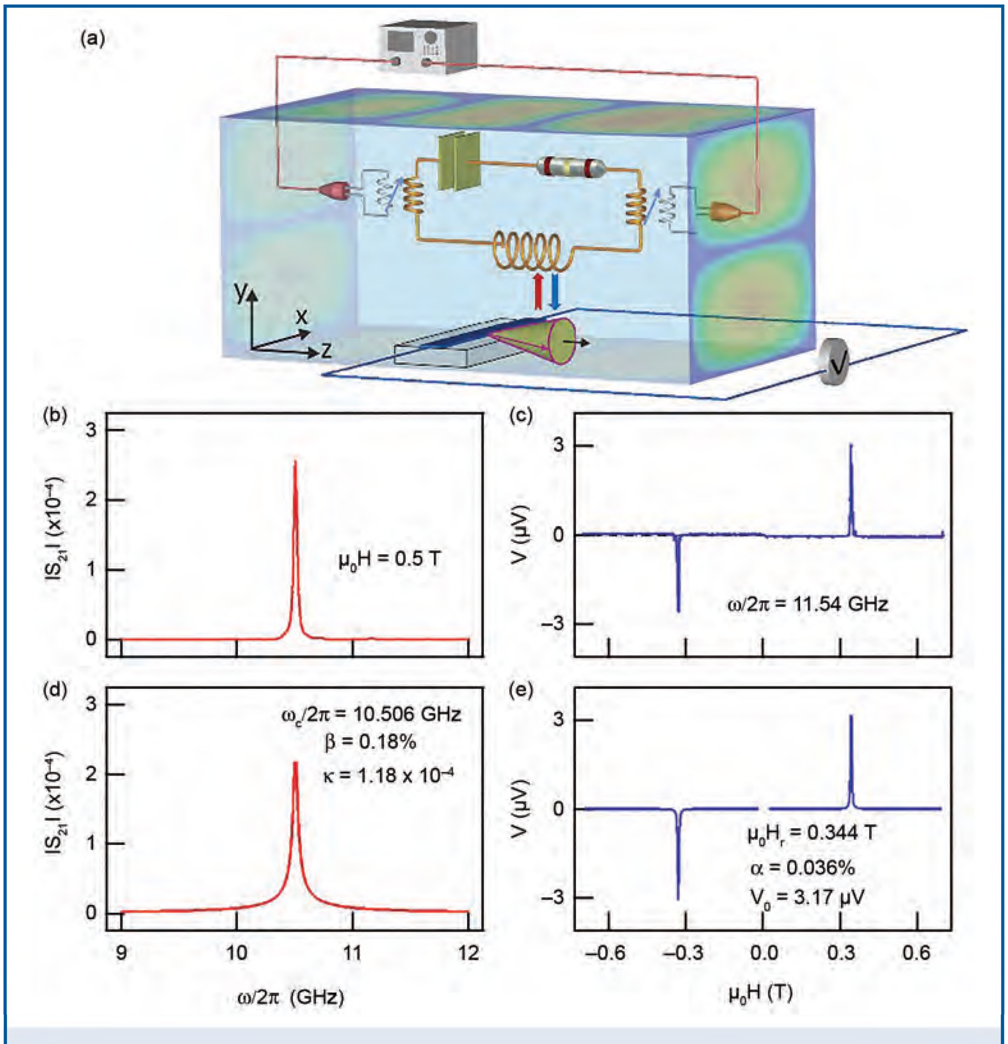


Fig. 1 Electrical detection of the cavity magnon polariton (adopted from [24]). (a) Sketch of the experimental setup and theoretical model for studying the cavity magnon polariton (CMP). The artificial *LCR* circuit models the microwave current carried by the cavity mode, which couples with the magnons in the magnetic material. Such a CMP can be detected by measuring (b) microwave transmission, and (c) photo-voltage. (d) and (e) are the theoretical results.

magnon-photon coupling experiments were initially performed at extremely low temperatures.

Tang *et al.*'s experimental result came as a big surprise. Not only did they demonstrate that the ultrastrong coupling regime can be reached at room temperature, but they also observed directly in the time domain up to 10 cycles of microwave oscillations induced by the magnon-photon coupling. Something must be happening beyond the scope of the quantum map, but the origin of classical magnon-photon coupling was not clear.

That mystery was solved by the Manitoba-Delaware collaboration [24], which singled out the classical origin of magnon-photon coupling: the phase correlation between FMR and the cavity resonance due to classical electrodynamics. Quantum coherence stems from entangled states evolving according to Schrodinger's equation, but Maxwell's equations of macroscopic electromagnetic fields also contain classical coherence. The close resemblance between Schrodinger's equation and Maxwell's equations indicates that the magnon-photon coupling can be either modeled as the quantum coherence of the entangled spin-photon states [15], or be described as the classical coherence of macroscopic electromagnetic fields [24]. In light of the classical map [24] of the cavity spintronics, an intriguing question arises of how to properly distinguish the quantum and classical regimes for the coupled magnon-photon system. New experiment is designed to search for exclusive quantum features [26]. In modern physics, probing the quantum superposition principle at the borderline to classical physics has been a powerful driving force [10,11]. Now, cavity spintronics adds new fuel to this engine.

THE RENAISSANCE OF CAVITY POLARITONS

The classical map [24] also leads to another insight. It shows that the eigenvector of the coupled magnon-photon mode is a linear combination of the rf magnetic field and rf magnetization. This is by definition the magnon-polariton [27]. Such a new insight links cavity spintronics with the physics of cavity polariton which is an exciting frontier of semiconductor research.

A polariton is an optical effect arising when light couples to a material that has a macroscopic polarization or magnetization. This concept was developed in 1951 by the 32-year-old Chinese physicist Kun Huang [28,29]. It was so fundamental that it soon became the "basic knowledge" of solid-state textbooks, which ubiquitously explains the interaction between electromagnetic waves and elementary excitations in materials such as phonons, excitons, and magnons [27].

A renaissance placing the polariton at the frontier of semiconductor research started in 1992 when C. Weisbuch *et al.* published an article [30] in *PRL*, showing that the strong coupling of the exciton and cavity photon in a semiconductor microcavity leads to the formation of a cavity exciton polariton, a half-light, half-matter bosonic quasi-particle. Since then, research in that frontier has led to remarkable breakthroughs in both basic and applied research, such as the discoveries of Bose-Einstein condensation [31] and superfluidity [32] of cavity exciton polaritons at standard cryogenic temperatures, the room-temperature polariton parametric scattering driven by a polariton condensate [33], and the development of the electrically pumped cavity polariton laser with unsurpassed properties based on the physics of coherent strong coupling [34].

So far, experiments on cavity polaritons are mainly performed in semiconductor materials at optical frequencies, utilizing the strong coupling of excitons with photons [30–34]. Now, the classical map of cavity spintronics reveals a new type of cavity polariton: the cavity magnon polariton [24] that is based on magnetic materials operating at microwave frequencies. Soon, the strong analogies between the polariton physics of the two different systems may merge the studies of cavity exciton polaritons with the growing interest in cavity magnon polaritons. This may not only lead to a better understanding of the fundamental physics of strong coupling between magnons and photons, but along such an adventure in basic research, new microwave and spintronic applications that are beyond our imagination will emerge.

CONCLUSION AND FUTURE PERSPECTIVES

In summary, advances in magnetism, nanotechnology, and light-matter interaction have created a new frontier of condensed matter research studying cavity spintronics. Via the quantum physics of spin-photon entanglement on the one hand, and via the classical coherence of electrodynamics on the other, this frontier merges the progress in spintronics with the advances in cavity QED and cavity polaritons. This brief article (with a more comprehensive version posted at arXiv:1508.01966) is focused on reviewing the root of this frontier by tracing it back to some of the most courageous, inspiring, and seminal work in the history of spintronics, cavity QED and polaritons.

Looking forward from the Canadian perspective, the development of cavity spintronics may benefit from the remarkable progress made by Canadian physicists and engineers, in the closely related fields of cavity optomechanics (developed by Mark Freeman, John Davis, Paul Barclay, Jack Sankey, and Aashish Clerk *et al.*, see the article *"Spin Mechanics"* by Losby and Freeman), quantum magnetism (studied by Chris Wiebe and Bruce Gaulin *et al.*), and miniaturized microwave circuits (invented by Lot Shafai and Greg Bridges *et al.*). With the wonderful twilight appearing in the dawn sky of cavity spintronics, perhaps an enjoyable way of imagining its future is listening to the song [35]:

I am the dawn, I'm the new day begun
I bring you the morning, I bring you the sun
I hold back the night and I open the skies
I give light to the world, I give sight to your eyes
I am the sky and the dawn and the sun

ACKNOWLEDGEMENTS

I would like to thank my co-workers L.H. Bai, M. Harder, B.M. Yao, S. Kaur, and Y.S. Gui for their contributions. I also thank my colleagues M. Johnson, J. Sirker, S. Goennenwein, H. Huebl, Y. Nakamura, H.X. Tang, T. Dietl, M. Freeman, H. Guo, J. Page, C. Schüller, Y. Xiao, J.Q. Xiao, W. Lu, and Z.H. Chen for discussions. Financial support from NSERC, CFI and NSFC are gratefully acknowledged.

REFERENCES

1. R.H. Silsbee, A. Janossy, and P. Monod, "Coupling between ferromagnetic and conduction-spin-resonance modes at a ferromagnetic-normal-metal interface", *Phys. Rev. B*, **19**, 4382 (1979).
2. Y. Tserkovnyak, A. Brataas, and G.E.W. Bauer, "Enhanced Gilbert damping in thin ferromagnetic films", *Phys. Rev. Lett.*, **88**, 117601 (2002); H.J. Jiao and G.E.W. Bauer, *Phys. Rev. Lett.*, **110**, 217602 (2013).
3. L. Berger, "Emission of spin waves by a magnetic multilayer traversed by a current", *Phys. Rev. B*, **54**, 9353 (1996); J. Slonczewski, *J. Magn. Magn. Mater.*, **159**, L1 (1996).
4. S.A. Wolf, *et al.*, "Spintronics: a spin-based electronics vision for the future", *Science*, **294**, 1488–1495 (2001).
5. M.N. Baibich, *et al.*, "Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices", *Phys. Rev. Lett.*, **61**, 2472 (1988).
6. M. Johnson and R.H. Silsbee, "Interfacial charge-spin coupling: injection and detection of spin magnetization in metals", *Phys. Rev. Lett.*, **55**, 1790 (1985).
7. F.J. Jedema, *et al.*, "Electrical detection of spin precession in a metallic mesoscopic spin valve", *Nature (London)*, **416**, 713 (2002).
8. W Hanle, "Über magnetische beeinflussung der polarisation der resonanzfluoreszenz", *Z. Phys.*, **30**, 93 (1924).
9. S.D. Bader and S.P. Parkin, "Spintronics", *Annu. Rev. Condens. Matter Phys.*, **1**, 71 (2010).
10. D.J. Wineland, "Nobel lecture: superposition, entanglement, and raising Schrödinger's cat", *Rev. Mod. Phys.*, **85**, 1103 (2013).
11. S. Haroche, "Nobel lecture: controlling photons in a box and exploring the quantum to classical boundary", *Rev. Mod. Phys.*, **85**, 1083 (2013).
12. C. Cohen-Tannoudji, *Atoms in Electromagnetic Fields*, World Scientific Series on Atomic, Molecular and Optical Physics - Vol. **3**, World Scientific Publishing Co. Pte. Ltd. 2004.
13. R. Laflamme, *et al.*, "Introduction to NMR quantum information processing", *Los Alamos Science*, **27**, 226–259 (2002).
14. A. Wallraff, *et al.*, "Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics", *Nature*, **431**, 162 (2004).
15. Ö.O. Soykal and M.E. Flatté, "Strong field interactions between a nanomagnet and a photonic cavity", *Phys. Rev. Lett.*, **104**, 077202 (2010).
16. H. Huebl, *et al.*, "High cooperativity in coupled microwave resonator ferrimagnetic insulator hybrids", *Phys. Rev. Lett.*, **111**, 127003 (2013).
17. Y. Nakamura, Y.A. Pashkin, and J.S. Tsai, "Coherent control of macroscopic quantum states in a single-cooper-pair box", *Nature*, **398**, 786–788 (1999).
18. Y. Tabuchi, *et al.*, "Hybridizing ferromagnetic magnons and microwave photons in the quantum limit", *Phys. Rev. Lett.*, **113**, 083603 (2014).
19. X. Zhang, *et al.*, "Strongly coupled magnons and cavity microwave photons", *Phys. Rev. Lett.*, **113**, 156401 (2014).
20. S. Holland, *et al.*, "Quantized dispersion of two-dimensional magnetoplasmons detected by photoconductivity spectroscopy", *Phys. Rev. Lett.*, **93**, 186804 (2004).
21. Y.S. Gui, S. Holland, M. Mecking, and C.-M. Hu, "Resonances in ferromagnetic gratings detected by microwave photoconductivity", *Phys. Rev. Lett.*, **95**, 056807 (2005).
22. Y.S. Gui, N. Mecking, X.Z. Zhou, G. Williams, and C.-M. Hu, "Realization of a room-temperature spin dynamo: the spin rectification effect", *Phys. Rev. Lett.*, **98**, 107602 (2007).
23. L.H. Bai, Y.S. Gui, and C.-M. Hu, *Electrical Detection of Ferromagnetic Resonance and Its New Applications in Spintronics*, in *Introduction to Spintronics*, edited by X. F. Han, Science Press, Beijing, 2014, Chap. **9**.
24. L. H Bai, M. Harder, Y.P. Chen, X. Fan, J.Q. Xiao, and C.-M. Hu, "Spin pumping in electrodynamically coupled magnon-photon systems", *Phys. Rev. Lett.*, **114**, 227201 (2015).
25. H. Huebl and S.T.B. Goennenwein, "Electrical signal picks up a magnet's heartbeat", *Physics*, **8**, 51 (2015).
26. Y. Tabuchi, *et al.*, "Coherent coupling between a ferromagnetic magnon and a superconducting qubit", *Science*, **24**, 405 (2015).
27. D.L. Mills and E. Burstein, "Polaritons: the electromagnetic modes of media", *Rep. Prog. Phys.*, **37**, 817 (1974).
28. K. Huang, "Lattice vibrations and optical waves in ionic crystals", *Nature*, **167**, 779 (1951).
29. K. Huang, "On the interaction between the radiation field and ionic crystals", *Proc. Royal. Soc. (London)*, **A208**, 352 (1951).
30. C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, "Observation of the coupled exciton-photon mode splitting in a semiconductor quantum microcavity", *Phys. Rev. Lett.*, **69**, 3314 (1992).
31. J. Kasprzak, *et al.*, "Bose–Einstein condensation of exciton polaritons", *Nature*, **443**, 409 (2006).
32. A. Amo, *et al.*, "Superfluidity of polaritons in semiconductor microcavities", *Nat. Phys.*, **5**, 805 (2009).
33. W. Xie, *et al.*, "Room-temperature polariton parametric scattering driven by a one-dimensional polariton condensate", *Phys. Rev. Lett.*, **108**, 166401 (2012).
34. C. Schneider, *et al.*, "An electrically pumped polariton laser", *Nature*, **497**, 348 (2013).
35. Celtic Woman, "*The sky and the Dawn and the Sun*", from the Album "The Greatest Journey – Essential Collections", Manhattan Records, 2008.