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ANALYSIS OF PATENT ACTIVITY IN THE FIELD OF QUANTUM INFORMATION PROCESSING

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This paper provides an analysis of patent activity in the field of quantum information processing. Data from the PatentScope database from the years 1993−2011 was used. In order to predict the future trends in the number of filed patents time series models were used.

Keywords: Quantum information processing; quantum computation; patinformatics.

1. Introduction

Quantum information science studies the application of quantum mechanics to processing, storing and transmitting information. The main trends of research involving theoretical aspects of quantum computing are: quantum information theory, quantum computation, quantum cryptography, quantum communication and quantum games. The origins of the field date back to the first decades of the 20th century, when the bases of quantum mechanics were formulated. The beginnings of quantum information theory can be traced back to von Neumann,[1] but the first established research in this area was conducted by Holevo[2] and Ingarden.[3]

In the last two decades of the 20th century, the groundwork for quantum computing was laid. First in the 80's, Bennett and Brassard,[4] then seven years later Ekert[5] discovered quantum key distribution (QKD) protocols. These research achievements gave rise to the whole new field of quantum cryptography. The Feynman's idea of quantum simulators[6] and Deutsch's work[7] on the universal quantum computer, followed by the discovery of the first quantum algorithms by Shor[8] and Grover[9] in the 90's of the 20th century created the whole new field of research on quantum computing and quantum algorithms. One of the promising areas of quantum information processing is quantum game theory initiated by Meyer[10] and then followed by Eisert *et al.*[11] at the turn of the century. Its application to quantum auctions was proposed later by Piotrowski and Sładkowski.[12]

At present it is hard to tell which specific physical system will be applied for the implementation of quantum information processing.[13] Among the most promising physical implementations one can point out cavity quantum electrodynamics,[14–16] trapped ions,[17,18] quantum optical lattices,[19–21] nitrogen-vacancy centers[22,23] and various realizations based on superconducting qubits.[24–29] However, it is believed that realistic systems capable of processing information according to the rules of quantum theory will be composed of diverse physical systems interacting with each other.[30] For this reason a significant amount of research has been dedicated to engineering the building blocks of quantum networks.[31–33]

2. Patent Analysis

The main goal of this work is to analyze and forecast patent activity in the field of quantum information processing. In order to reach this goal a statistical analysis of the patent database was made.

2.1. *Research methodology*

2.1.1. *Data source*

In order to gather patents covering quantum information processing the database of patent applications PatentScope,[34] which is made accessible by World Intellectual Property Organization, was used.

2.1.2. *Search methodology*

The PatentScope database allows searching in full text versions of patent applications at European, international and country levels. It allows searching in almost 11 million patent documents which includes 2 million of international patent applications.

In order to analyze patent documents which may concern quantum information processing, following queries to PatentScope database were performed.

1. “`quantum computer`” `OR` “`quantum computing`” `OR` “`quantum computation`” `OR` “`quantum compute`”
2. “`quantum communication`”
3. “`quantum information`”
4. `teleportation`
5. “`quantum bit`” `OR qubit OR qbit`
6. `quantum AND` “`random number generator`”
7. “`quantum cryptography`”
8. “`quantum key`” `AND (distribut* OR exchang*)`
9. “`quantum Fourier`”
10. “`quantum fast`” `OR` ”`fast quantum`”

11. `(quantum OR photo* OR optic*) AND BB84`
12. `quantum AND grover`
13. `quantum AND (“single photon source” OR “single-photon source” OR “single photon generator” OR “single-photon generator” OR “single photon detector”`
    `OR “single-photon detector”)`
14. `“quantum switch”`
15. `quantum AND spintronic*`

Selection of those queries was based upon previous work presented in Ref. 35. The PatentScope search engine was instructed to apply queries only to the front page of the patent text. The reason for this is that many patents mention quantum devices or qubits but they cannot be reasonably classified as concerning directly quantum information processing. The problem is discussed in the next subsection.

2.2. *Analysis of patents concerning quantum computing in the years 1993−2011*

Analysis of patent data is one of the most reputed methods of projecting technology development. Arguments supporting this claim were presented in Ref. 36. Application of time series methods for examining technology development was presented in details in work 37. In this report, methods of time series analysis are used to predict the development of quantum information processing technologies.

The analysis was performed on 522 patents selected from the PatentScope database. For the analysis, only the data from years 1993−2011 was taken into account. Data from year 2012 was rejected due to its incompleteness at the time when this analysis was performed. After analyzing IPC categories, the number of patents in institutions and the geographic scope of the patents one can draw the following conclusions.

2.2.1. *Patents classification*

In Fig. 1, we have gathered the numbers of patents belonging to classes of the IPC classification. Relevant IPC codes are listed in Table 1. Note that one patent may belong to several classes. Most of the patents belong to class H04L covering “Transmission of digital information”, two other dominant classes are H04K — “Secret communication; jamming of communication” and H01L — “Semiconductor devices; electric solid state devices not otherwise provided for”.

2.2.2. *Applicants*

The number of patents owned by patent holder is presented in Table 2. Its analysis shows that intellectual property in the field of quantum information processing is highly scattered. Almost half of the patents are owned by business organizations or research institutes that have filed up to five patents each. Two major firms which are

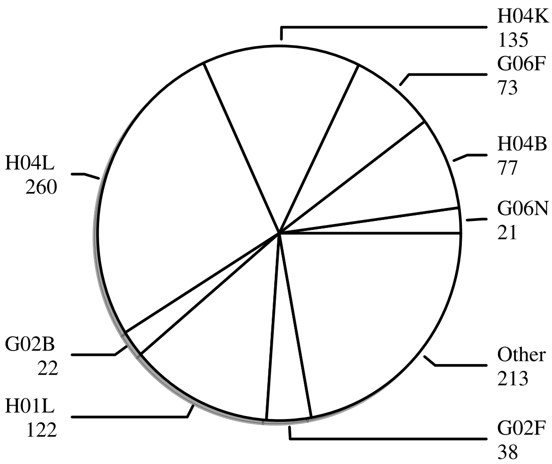

Fig. 1. Groups of patents according to the IPC classification. One patent can be included into more than one categories.

focused on the area of quantum information processing, namely MagiQ Technologies Inc. and D-Wave Systems, own more than 100 quantum information patents.

2.2.3. *Patents by region*

In Table 3, we present the numbers of patents filed in each of the regions. More than half of the patents were international applications filed under the Patent Cooperation Treaty (marked as region WO), 163 patents were filed with the European Patent Office and 51 patents were filed in the Republic of Korea.

2.2.4. *The Nokia case*

It can be observed that there is a trend to extend patent claims so that embodiments of a method include implementation using quantum information. As an example,

Table 1. IPC codes.

G02B	Optical Elements, Systems or Apparatus
G06F	Electric Digital Data Processing
H04B	Transmission
H04K	Secret Communication; Jamming of Communication
H04L	Transmission of Digital Information, e.g. Telegraphic Communication
H01L	Semiconductor Devices; Electric Solid State Devices not otherwise Provided For
G06N	Computer Systems Based on Specific Computational Models
G02F	Devices or Arrangements, The Optical Operation of Which is Modified by Changing The Optical Properties of the Medium of the Devices or Arrangements for the Control of the Intensity, Color, Phase, Polarization or Direction of Light, e.g. Switching, Gating, Modulating or Demodulating; Techniques or Procedures for the Operation Thereof; Frequency-Changing; NonLinear Optics; Optical Logic Elements; Optical Analogue/Digital Converters

Table 2. The number of patents owned by corporations and research institutes.

Company	No of patents	Percentage
D-Wave	57	11.0%
Magiq Technologies Inc	52	10.0%
Hewlett−Packard	31	6.0%
Qinetiq Limited	25	5.0%
Mimos Berhad	24	5.0%
British Telecommunications	19	4.0%
Electronics and Telecommunications Research Institute	13	2.0%
Unisearch Limited	13	2.0%
Japan Science and Technology	10	2.0%
Mitsubishi Denki Kabushiki Kaisha	10	2.0%
The Johns Hopkins University	9	2.0%
Northrop Grumman Systems Corporation	9	2.0%
The Chinese University of Hong Kong	9	2.0%
Lucent Technologies Inc	7	1.0%
Nec Corporation	7	1.0%
Thales	6	1.0%
Qucor Pty Ltd	5	1.0%
Other	216	41.0%

Table 3. The number of patents by region.

Code	Region	Number of patents
WO	World Intellectual Property Organization	291
EP	European Patent Office	163
KR	Republic of Korea	51
RU	Russian Federation	5
ZA	South Africa	3
IL	Israel	3
ES	Spain	3
SG	Singapore	2
MX	Mexico	1

Nokia includes such claims in their inventions e.g. image analysis. For example, in patent[38] one can read as follows:

> "Computer system 900 is programmed (e.g. via computer program code or instructions) to detect a face portion in a frame of a plurality of frames in a multimedia content of a device, track the face portion and perform color-tracking on losing a track of the face portion for re-tracking the face portion, as described herein and includes a communication mechanism such as a bus 910 for passing information between other internal and external components of the computer system 900. Information (also called data) is represented as a physical expression of a measurable phenomenon, typically electric voltages, but including, in other embodiments, such phenomena as magnetic, electromagnetic, pressure, chemical, biological,

> molecular, atomic, sub-atomic and quantum interactions. For example, north and south magnetic fields, or a zero and nonzero electric voltage, represent two states (0, 1) of a binary digit (bit). Other phenomena can represent digits of a higher base. *A superposition of multiple simultaneous quantum states before measurement represents a quantum bit* (*qubit*)".

The last quoted sentence can be found in 257 patents filled by Nokia Corporation and in several patents filed by other applicants. In patents filed in the year 2009 this sentence can be found in three documents, in the year 2010 in 54, in the year 2011 in 102 and in the year 2012 in 111. It seems that in 2009 organizations started to believe that the realization of a quantum computing system was actually possible.

3. Models and Trends

3.1. *Models of time series for the number of filed patents by year*

In order to model the number of filed patents by year, four types of statistical models, described below, were applied. A similar analysis for patents covering the area of biotechnologies was presented in work 39.

3.1.1. *Linear regression*

Linear regression finds linear dependency between a pair of variables. The linear regression model is in the following form:

$$y_i = \alpha + \beta x_i + e_i, \tag{1}$$

where x_i and y_i are dependent variables, α and β are intercept and slope parameters, respectively, e_i is model error i.i.d. Normal with mean 0 and constant variance σ^2.

3.1.2. *Poisson regression*

Poisson regression is a form of regression analysis used to model observations which can take only non-negative integer values, e.g. count data. It is assumed, that the distribution of the response variable Y is given by Poisson distribution:

$$P(Y = k) = e^{-\lambda} \frac{\lambda^k}{k!}, \tag{2}$$

for a positive parameter λ. Poisson regression is often called the log-linear model.

3.1.3. *Auto-regression moving average models*

Auto-regression moving average (ARMA) model is fitted to time series data either to forecast future points in the series or to better understand the data. ARMA models constitute one of the most general classes of time series forecasting models, they are applied in cases where data shows stationarity. A detailed description of this model can be found in the book.[40]

3.1.4. *Support vector regression model*

The idea of support vector regression (SVR) is based on the designation of the linear regression function in a space of higher dimension than the original data. Mapping to the high-dimensional space is performed by means of nonlinear functions. The SVR method has been successfully used in various fields, such as time series and forecasting of financial data, approximations of solutions of complex engineering analyses, convex and quadratic programming, etc. The theory for this method was originally developed by Vapnik and his colleagues in laboratories AT&T Bell[41–43] for the purpose of classification. However, it is possible to use this method for regression problems.[44]

3.2. *Results*

Figure 2 presents the number of reported patents in years from 1993 to 2011. The above mentioned models were fitted to the data and an extrapolation was made to the year 2015.

3.2.1. *Fitting of the models*

The first step in the analysis was to perform linear and Poisson regressions, thus the intercept and slope parameters were determined. Additionally for linear regression the coefficient of determination R^2 was calculated. The results of the analysis are presented in Table 4. The AIC column stands for the *Akaike factor*, derived from the *Akaike Information Criterion* and can serve as a measure of quality of the regression models fitting. Graphical representation of the linear and Poisson regression model fitted to the data is presented in Figs. 3(a) and 3(b), respectively.

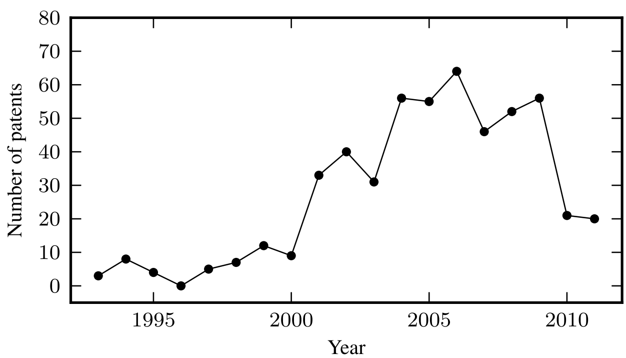

Fig. 2. The number of patents in years 1993−2011.

Table 4. Results for regression models.

Regression model	α	β	R^2	AIC
Linear	2.78	$-5.55 \cdot 10^3$	0.505	163.08
Poisson	$1.08 \cdot 10^{-1}$	$-2.14 \cdot 10^2$	—	283.57

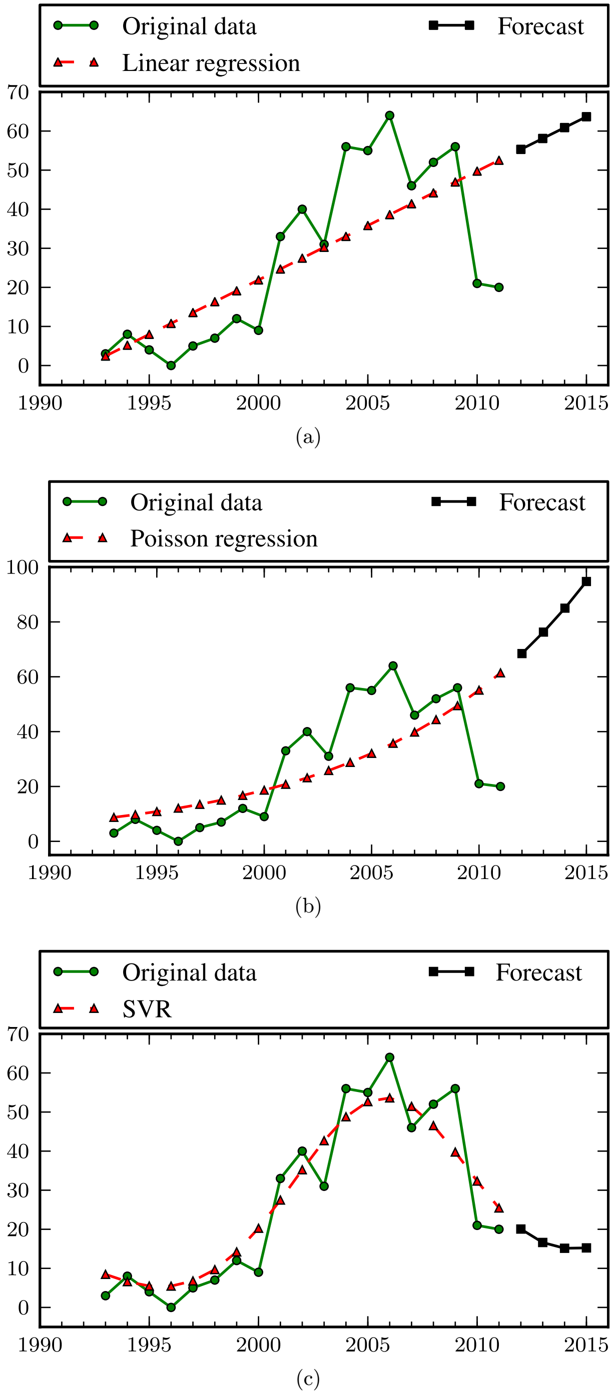

Fig. 3. Model fitting and forecast of the number of patents filed in a given year on the basis of linear regression, Poisson regression and SVR.

Table 5. Comparison of the quality of fitting for different models.

Model	RMSE
Poisson regression	17.81
Linear regression	15.1
SVR	7.4
ARMA(0, 1)	12.44
ARMA(0, 2)	12.42
ARMA(1, 0)	12.03
ARMA(1, 1)	12.03
ARMA(1, 2)	9.88
ARMA(2, 0)	12.03
ARMA(2, 1)	10.53
ARMA(2, 2)	11.15

In the next step, SVR models were considered, for which RBF (called the *radial basis function*) with $\gamma = 1$ was used as the kernel function. Fitting of the described model is presented in Fig. 4.

In the last step, ARMA models were considered for different model parameters. The fitting of the ARMA models to the patent data was also presented graphically in Fig. 3(c).

On analyzing the root mean square error (RMSE) ratio, it can be seen that the best fit is obtained for SVR models. The summary of RMSE values for the considered models is presented in Table 5.

3.2.2. *Forecast based on the introduced models*

In Figs. 3 and 4, forecast of the number of filed patents in the years 2012−2015 based on the aforementioned models are plotted. The model which has the best fit, i.e. the SVR model, projects stabilization of the number of patents per year at the level of below 20. The linear model forecasts that in the year 2015 approximately 65 patents will be filed. The Poisson regression model envisages an exponential increase in the number of patents, however, the estimated values are unlikely because of high RMSE — the highest among the used models. All fitted ARMA models, except ARMA(1,2), predict an increase in the number of filed patents. The ARMA(1,2) model, which has the lowest RMSE among ARMA models, predicts a slight decrease and a subsequent increase after the year 2013.

4. Summary

We have provided an analysis of patent activity in the field of quantum information processing. One can notice an increase in patent activity in the years 2001−2009. In subsequent years, the activity sharply decreased. In order to predict the future activity we have used several models to estimate the number of patents to be filed

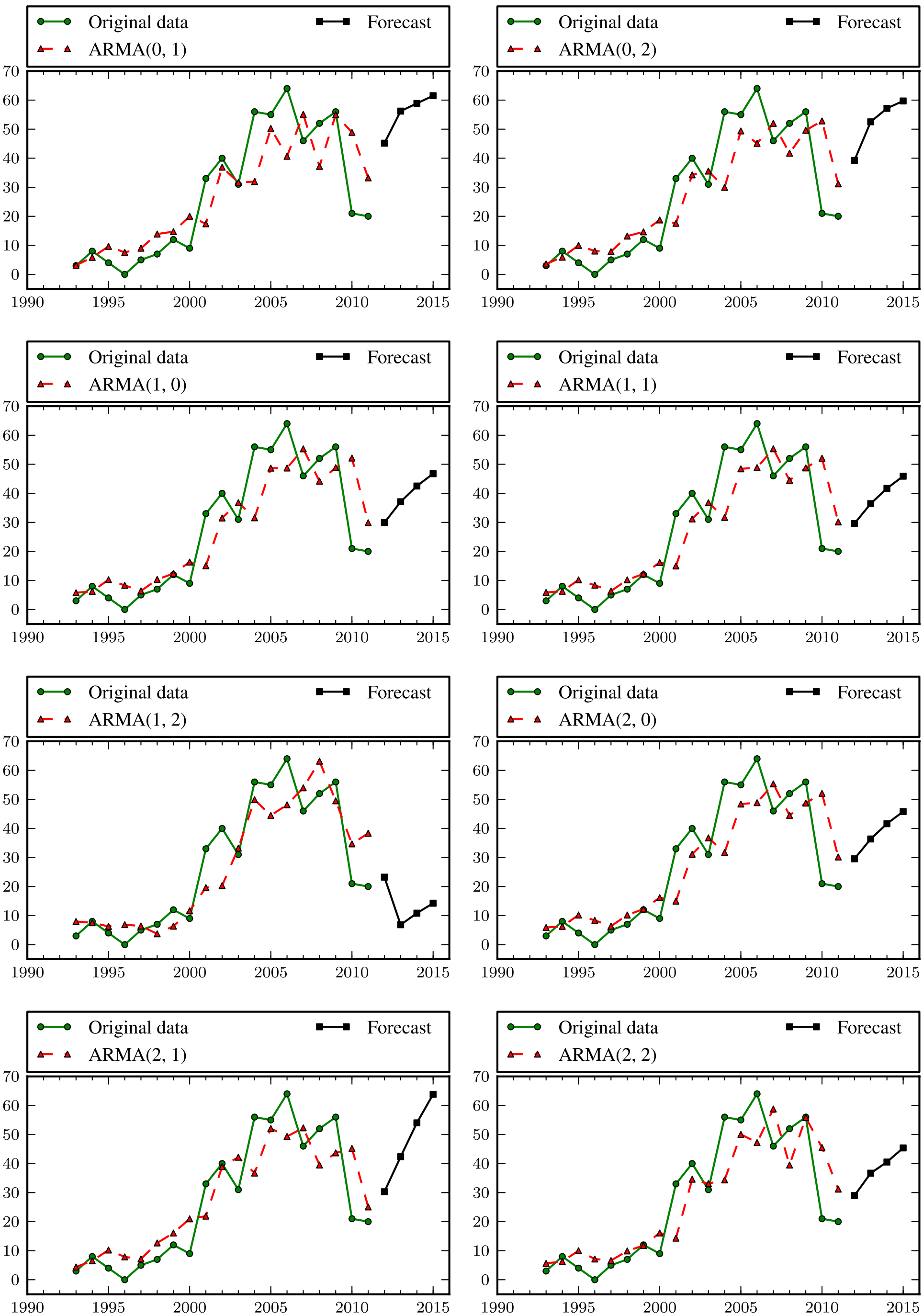

Fig. 4. Model fitting and forecast of the number of patents filed in a given year on the basis of ARMA models.

until the year 2015. Both models with low error — SVR and ARMA(1,2) — predict that around 15 patents will be filed in 2015.

Acknowledgments

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References

1. J. Von Neumann, *Göttinger Nachrichten* **1** (1927) 273.
2. A. S. Holevo, *Probl. Inform. Transm.* **9** (1973) 31 (in Russian).
3. R. S. Ingarden, *Quantum Inform. Theory.* **10** (1976) 43.
4. C. H. Bennett, G. Brassard *et al.*, Quantum cryptography: Public key distribution and coin tossing, in *Proc. IEEE Int. Conf. Computers, Systems and Signal Processing*, Vol. 175, Bangalore, India (1984).
5. A. K. Ekert, *Phys. Rev. Lett.* **67** (1991) 661.
6. R. P. Feynman, *Int. J. Theor. Phys.* **21** (1982) 467.
7. D. Deutsch, *Proc. R. Soc. London A. Math. Phys. Sci.* **400** (1985) 97.
8. P. W. Shor, Algorithms for quantum computation: Discrete logarithms and factoring, in *Foundations of Computer Science, 1994 Proceedings, 35th Annual Symposium*, IEEE, (1994), pp. 124−134.
9. L. K. Grover, A fast quantum mechanical algorithm for database search, in *Proc. Twenty-Eighth Annual ACM Symp. Theory of Computing*, ACM (1996), pp. 212−219.
10. D. A. Meyer, *Phys. Rev. Lett.* **82** (1999) 1052.
11. J. Eisert, M. Wilkens and M. Lewenstein, *Phys. Rev. Lett.* **83** (1999) 3077.
12. E. W. Piotrowski and J. Sładkowski, *Physica A: Stat. Mech. Appl.* **312** (2002) 208.
13. P. Hemmer and J. Wrachtrup, *Science* **324** (2009) 473.
14. H. Walther, B. T. H. Varcoe, B.-G. Englert and T. Becker, *Rep. Progr. Phys.* **69** (2006) 1325.
15. R. Miller, T. E. Northup, K. M. Birnbaum, A. Boca, A. D. Boozer and H. J. Kimble, *J. Phys. B At. Mol. Opt. Phys.* **38** (2005) S551.
16. A. Stute, B. Casabone, B. Brandstätter, D. Habicher, H. G. Barros, P. O. Schmidt, T. E. Northup and R. Blatt, *Appl. Phys. B* **107** (2012) 1145.
17. J. Kim and Ch. Kim, *Quantum Inform. Comput.* **9** (2009) 0181.
18. T. Monz, P. Schindler, J. T. Barreiro, M. Chwalla, D. Nigg, W. A. Coish, M. Harlander, W. Hänsel, M. Hennrich and R. Blatt. *Phys. Rev. Lett.* **106** (2011) 130506.
19. G. K. Brennen, C. M. Caves, P. S. Jessen and I. H. Deutsch, *Phys. Rev. Lett.* **82** (1999) 1060.
20. T. C. Li, H. Kelkar, D. Medellin and M. G. Raizen, *Opt. Express* **16** (2008) 5465.
21. M. S. Everitt, M. L. Jones, B. T. H. Varcoe and J. A. Dunningham, *J. Phys. B: At. Mol. Opt. Phys.* **44** (2011) 035504.
22. M. V. Gurudev Dutt, L. Childress, L. Jiang, E. Togan, J. Maze, F. Jelezko, A. S. Zibrov, P. R. Hemmer and M. D. Lukin, *Science* **316** (2007) 1312.

23. P. C. Maurer, G. Kucsko, C. Latta, L. Jiang, N. Y. Yao, S. D. Bennett, F. Pastawski, D. Hunger, N. Chisholm, M. Markham, D. J. Twitchen, J. I. Cirac and M. D. Lukin, *Science* **336** (2012) 1283.
24. A. N. Jordan and M. Büttiker, *J. Mod. Opt.* **51** (2004) 2405.
25. L. Chirolli and G. Burkard, *Phys. Rev. B* **74** (2006) 174510.
26. A. A. Houck, J. Koch, M. H. Devoret, S. M. Girvin and R. J. Schoelkopf, *Quantum Inform. Process.* **8** (2009) 105.
27. N. Grønbech-Jensen, J. E. Marchese, M. Cirillo and J. A. Blackburn, *Phys. Rev. Lett.* **105** (2010) 010501.
28. C. Rigetti, J. M. Gambetta, S. Poletto, B. L. T. Plourde, J. M. Chow, A. D. Córcoles, J. A. Smolin, S. T. Merkel, J. R. Rozen, G. A. Keefe, M. B. Rothwell, M. B. Ketchen and M. Steffen, *Phys. Rev. B* **86** (2012) 100506.
29. V. M. Stojanović, A. Fedorov, A. Wallraff and C. Bruder, *Phys. Rev. B* **85** (2012) 054504.
30. H. J. Kimble, *Nature* **453** (2008) 1023.
31. Ch. Clausen, I. Usmani, F. Bussiéres, N. Sangouard, M. Afzelius, H. de Riedmatten and N. Gisin, *Nature* **469**(7331) (2011) 508.
32. M. A. Hall, J. B. Altepeter and P. Kumar, *Phys. Rev. Lett.* **106** (2011) 053901.
33. I. Choi, R. J. Young and P. D. Townsend, *New J. Phys.* **13** (2011) 063039.
34. PatentScope, Available at http://patentscope.wipo.int/. Last accessed on July 2, 2012.
35. M. C. Chang. Quantum computation patent mapping-a strategic view for the information technique of tomorrow, in *Services Systems and Services Management, 2005. Proc. ICSSSM'05. 2005 International Conference on*, Vol. 2, IEEE (2005), pp. 1177−1181.
36. B. H. Hall, A. B. Jaffe and M. Trajtenberg, The NBER patent citation data file: Lessons, insights and methodological tools, Technical report, National Bureau of Economic Research (2001).
37. H. Dernis and D. Guellec, *STI-Sci. Technol. Ind. Rev.* **27** (2000) 129.
38. V. Muninder, P. Mishra, C.-Y. Jo and K. Govindarao (2011). WIPO Patent No. WO/2011/161307. Geneva, Switzerland: World Intellectual Property Organization.
39. S. Jun and D. Uhm, *J. Mod. Math. Stat.* **4** (2010) 101.
40. P. J. Brockwell and R. A. Davis, *Time Series: Theory and Methods* (Springer Verlag, 2009).
41. V. Vapnik. *Autom. Remote Contr.* **24** (1963) 774.
42. V. Vapnik and A. Chervonenkis. *Autom. Remote Contr.* **25** (1964).
43. V. Vapnik, S. E. Golowich and A. Smola, *Adv. Neural Inf. Process. Syst.* **9** (1996) 281.
44. R. S. Tsay, *Analysis of Financial Time Series*, Vol. 543 (Wiley-Interscience, 2005).