

# **Marie Curie ITN cQOM**

## **Summary of the Scientific Achievements**

**Name of Fellow: Muhammad Asjad**  
**Principal Investigator: Prof. David Vitali**  
**Academic / Industrial Institution: University of Camerino**  
**Start Date of ITN Fellowship: 01-08-2013**  
**End Date of ITN Fellowship: 31-05-2016**  
**Date of Report: 20-06-2016**

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### **1. Description of research work**

My theoretical research work is focused on the study of quantum effects in cavity optomechanical systems by exploiting the radiation pressure interaction of a high-finesse multimode optical cavity with a thin dielectric membrane inside and its possible variations. We focus on the applications of these systems to quantum information tasks and protocol, requiring the generation and manipulation of entanglement between optical, electrical and mechanical degrees of freedom.

### **2. Goals achieved and/or progress towards them**

The performance of various optomechanical schemes for the realization of quantum states of nanomechanical degrees of freedom, such as squeezed and Schroedinger cat states, are analyzed, paying also attention to their potential for measurements below the standard quantum limit. A scheme to construct a quantum phase gate with an optomechanical system with conditional phase shift “ $\pi$ ” between two optical qubits associated with two cavity modes have been proposed. We have also studied a scheme to realize the steady state entanglement between two output modes of a hybrid optomechanical system driven by optical fields. We showed that this optical-optical entanglement is useful for long distance secure quantum communication, and that one can enhance this output entanglement by using a closed loop feedback based on homodyne measurement. Moreover, we have proposed a scheme for the generation of stationary entanglement between two mechanical resonators beyond the resolved sideband regime in the presence of an input squeezed driving field.

### **3. Training received (complementary/soft skills, ITN workshops attended)**

Since August 2013, I am in Camerino full-time as a Marie Curie fellow. I have attended many local and international workshops, conferences and schools, where I presented my work and met many well experienced researchers. Participations in these activities improved my communication skills and I expect to be able to communicate efficiently scientific results to both experienced researchers and general audience.

### **4. Participation and role in dissemination and outreach activities**

I participated to the 5<sup>th</sup> Scientific day (2015 and 2016) at UNICAM, presenting posters regarding my work on non-classical states of a nano-mechanical resonator.

I have also attended several transferable skills activities organized every year by the UNICAM School of Advanced Studies (SAS), i.e., the UNICAM PhD School. In particular, I have attended short courses on how to improve communication skills, on patenting the results of scientific activity, on how to write a successful research proposal, and a course on conveying scientific results to the general community. I have attended the seminars illustrating the European programs for research development within Horizon2020.

## 5. List of conferences attended

- I have participated to the workshop on “Fundamental noise sources”, in Mardorf (Germany) on 16.-20. June 2013.
- I have participated to the “Workshop on Quantum Nano-and Micromechanics” (21.-25. July 2013) at Monte Verita, Switzerland.
- I have presented my work at the “Workshop on Theory of cavity optomechanics” (7.-9. October, 2013) at the University of Erlangen (FAU), Erlangen, Germany.
- I have participated at the “Workshop on Taking an idea to a product” (10. October, 2013) at attocube systems GmbH, Munich, Germany.
- I have participated at the “Workshop on Cavity Optomechanics – from the micro- to the macro scale” (4.-6. November 2013) at Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria.
- I have participated at the “Workshop on Experimental toolbox for cavity optomechanics” (02.-04. April 2014) at Pierre and Marie Curie University (UMPC), Paris, France.
- I have participated at the “Workshop on Finite Element Modeling Workshop” (21-23 July 2014) at Swiss Federal Institute of Technology in Lausanne (EPFL), Lausanne, Switzerland.
- I have presented my work at “cQOM Diavolezza workshop” (1-5, Feb 2015) at Diavolezza, Switzerland.
- I have attended the “Les Houches Summer School on Quantum Optomechanics and Nanomechanics” (03-28 Aug 2015) at Les Houches, France.
- I have participated at the Workshop “Taking a Research Idea to a Product” (30 Nov - 1 Dec 2015) at Rüşchlikon, Switzerland.

## 6. Publications (with links)

- M. Asjad, P. Tombesi, D. Vitali. “**Feedback Control of Two-mode Output Entanglement and Steering in Cavity Optomechanics.**” [arXiv:1604.00399](https://arxiv.org/abs/1604.00399) (2016)
- M. Asjad, S. Zippilli, D. Vitali. “**Mechanical Einstein-Podolsky-Rosen entanglement with a finite-bandwidth squeezed reservoir.**” *Physical Review A* 89, 023849 (2016). <http://dx.doi.org/10.1103/PhysRevA.93.062307> .
- M. Asjad, S. Zippilli, P. Tombesi, D. Vitali. “**Large distance continuous variable communication with concatenated swaps.**” *Phys. Scr.* **90**, 074055, (2015). [10.1088/0031-8949/90/7/074055](https://doi.org/10.1088/0031-8949/90/7/074055) .

- M. Asjad, P. Tombesi, D. Vitali. **“Quantum phase gate for optical qubit with cavity quantum optomechanics.”** Optics Express, vol. 23, 7786 (2015). [10.1364/OE.23.007786](https://doi.org/10.1364/OE.23.007786) .
- M. Asjad, G. S. Agarwal, M. S. Kim, P. Tombesi, G. Di Giuseppe, D. Vitali. **“Robust stationary mechanical squeezing in a kicked quadratic optomechanical system.”** Physical Review A 89, 023849 (2014). [10.1103/PhysRevA.89.023849](https://doi.org/10.1103/PhysRevA.89.023849) .
- M. Asjad, D. Vitali. **“Reservoir engineering of a mechanical resonator: generating a macroscopic superposition state and monitoring its decoherence.”** Journal of Physics B: Atomic, Molecular and Optical Physics 47, 045502 (2014). [10.1088/0953-4075/47/4/045502](https://doi.org/10.1088/0953-4075/47/4/045502) .

## 7. Career plans after ITN

I will complete my PhD at the university of Camerino in October 2016 and search for a postdoc position. After that my intention is to remain in academia and in the field related to cavity quantum optomechanics, which I think has the potential to become an important scientific and technological field,