EVALUATION OF GLASS NANO/MICROSTRUCTURES REPLICATION FIDELITY AFTER LASER-ASSISTED HOT EMBOSSING PROCESS

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Peranti kaca optik dengan struktur mikro/nano berpotensi digunakan dalam pelbagai aplikasi antaranya dalam bidang pengimejan, ujian berdekatan pesakit bagi diagnostik perubatan, permukaan berinspirasikan alam semulajadi dan juga biosensor. Percetakan termal ialah satu teknik pembuatan yang mudah, menjimatkan dan efisien untuk penghasilan kaca optik berstruktur mikro/nano. Walaubagaimanapun, proses percetakan termal konvensional memerlukan kitaran termal yang panjang, kesukaran mendapatkan corak berkualiti tinggi terutamanya bagi corak kecil bersaiz sub-mikron, dan penipisan ketebalan kaca yang berlebihan. Sehingga kini, penghasilan peranti mikro/nano berasaskan kaca berkualiti tinggi menggunakan percetakan konvensional masih mencabar. Bagi menambah baik proses sedia ada, bantuan penggunaan ultrasonik, elektrik atau laser semakin mendapat perhatian. Walaupun percetakan termal terbantu laser sangat berpotensi menjadi satu kaedah baru bagi percetakan terus, pantas dan luas, merealisasikannya untuk penggunaan praktikal tetap mencabar. Ini kerana terdapat pelbagai parameter yang perlu dipertimbangkan antaranya tenaga laser, kelajuan pengimbasan laser, beban percetakan dan suhu pemanasan awal. Dalam kajian ini, percetakan termal terbantu laser yang membolehkan percetakan pantas pelbagai corak kecil bersaiz mikro dan nano ke atas permukaan kaca optik K-PG375, dengan keseluruhan kitaran proses yang lebih pendek dicadangkan. Kesan parameter percetakan termal terbantu laser kepada kualiti corak kaca yang direplikasi disiasat secara teliti. Selain itu, faktor seperti saiz dan bentuk corak serta nisbah ketinggian kepada lebar corak kepada aliran kaca juga dianalisis. Kaedah ini memanfaatkan sinergi daripada ketelusan acuan silikon dan penyerapan tenaga pada permukaan kaca yang sangat tinggi pada gelombang 10.6 μm. Tenaga yang diserap menghasilkan pemanasan yang ketara pada permukaan kaca, mengurangkan kelikatan permukaan kaca dan mempercepatkan pengisian bahan kaca ke dalam rongga acuan berstuktur nano/mikro. Keputusan menunjukkan dengan kawalan parameter seperti kelajuan pengimbasan laser, suhu pra-pemanasan dan beban, pelbagai corak berkualiti tinggi seperti garis, lubang dan tiang, lebar corak antara 225 nm ke 50 μm, telah berjaya direplikasi ke permukaan kaca optik dengan sangat pantas, serta-merta terhasil selepas setiap imbasan laser. Pemindahan corak terhasil apabila kelajuan pengimbasan laser berlaku antara 5 mm/s ke 25 mm/s, suhu pra-pemanasan dalam julat 320°C ke 335°C dan beban dalam julat 0.2 MPa ke 0.5 MPa. Juga didapati nisbah pengisian bertambah baik apabila kelajuan pengimbasan berkurangan. Pada kelajuan pengimbasan 30 mm/s, replikasi gagal kerana kenaikan suhu yang tidak mencukupi pada permukaan kaca, Apabila kelajuan pengimbasan dikurangkan kepada 1 mm/s, beberapa masalah seperti penipisan kaca yang berlebihan, lekatan kuat kaca ke acuan atau keretakan berlaku. Apabila nisbah ketinggian kepada lebar corak acuan meningkat, ketinggian corak kaca yang direplikasi juga berkurangan. Sebagai contoh praktikal, prestasi optik kaca sebagai peranti optik difraktif dan penapis optik resonan mod berpandu juga ditunjukkan. Jarak dan susunan parut difraktif yang diukur selepas disinari oleh sumber laser adalah sepadan dengan pengiraan teori. Seterusnya, penggunaannya sebagai penapis optik resonan mod berpandu juga telah dinilai. Nilai spektrum puncak yang diperoleh adalah memuaskan; yang menghasilkan purata lebar penuh pada separuh maksimum dan nilai panjang gelombang puncak masing-masing pada 4.6 nm dan 691.39 nm. Secara keseluruhannya, teknik yang dicadangkan berupaya menjadi satu pendekatan yang lebih mudah, menjimatkan dan pantas bagi penghasilan corak kejuruteraan bersaiz skala nano/mikro ke atas permukaan kaca bagi pelbagai aplikasi optik.

ABSTRACT

Micro/nanostructured glass allows the realization of many optical devices potentially exploited in numerous applications, such as in the field of imaging, point-of-care testing (POCT) for medical diagnostics, bio-inspired surfaces, and biosensors. Hot embossing is a simple, low-cost and efficient method for fabricating glass micro/nanostructures. Nevertheless, the existing hot embossing process suffers from a long thermal cycle, poor replication fidelity, especially for sub-micron features, and excessive glass thickness reduction. To date, it is still challenging to fabricate glass-based micro/nanodevices of high quality efficiently by using conventional hot embossing. To improve the process, the application of an external source to supplement the hot embossing process, such as ultrasonic, electrical, or laser-assisted means is gaining interest. Despite the potentials of laser-assisted hot embossing as a direct, rapid, and large area patterning method, its realization for practical application is still challenging. Various parameters need to be considered during the laser-assisted hot embossing process, including laser energy density, laser scanning speed, imprinting load and preheating temperature. This study proposed a laser-assisted hot embossing method that enables rapid imprinting of various micro and nanoscale patterns on K-PG375 optical glass substrates, with a shorter overall thermal cycle. The effect of laser-assisted scanning hot embossing parameters on the embossed glass pattern width, height and shape was investigated. Furthermore, the effects of mold pattern aspect ratio on the replication height of the embossed glass was analyzed. This method utilized the synergy of silicon mold high transmittance and strong optical absorption of glass at wavelength of 10.6 μm. The glass absorbed photon energy provided substantial heating of the glass surfaces, thus reducing the glass surface viscosity and accelerating the glass material filling in micro/nanostructure mold cavities. The results revealed that by controlling related parameters, such as laser scanning speed, preheating temperature, and pressing load, various high-resolution periodic grating, hole, and pillar patterns can be obtained. Pattern width ranging from 225 nm up to 50 μm, was successfully copied to the glass surface with a very short contact pressing time, instantaneously after each laser pass. Pattern transfer occurred when the scanning speed varied between 5 mm/s and 25 mm/s, preheating temperature in the range of 320°C to 335°C and moderate load in the range of 0.2 MPa to 0.5 MPa. It was found that the filling ratio improved as the scanning speed decreased. At a scanning speed of 30 mm/s, the replication failed due to insufficient temperature rise at the glass surface. When the scanning speed was reduced to 1 mm/s, several problems such as excessive deformation in the bulk glass and strong stiction of glass to the mold after demolding or glass cracking was observed. It was clearly observed that, as the aspect ratio increased, the average replication height of embossed glass decreased. As proof of concept, the optical performance of fabricated glass as diffractive optical elements and optical filter for guided mode resonant was also demonstrated. The measured diffractive grating spacing and order after illuminated by laser source were in good agreement with the theoretical calculation. In the latter, the utility of laser-assisted, imprinted glass nanostructures as guided mode resonant (GMR) optical filter was evaluated. The peak spectral values obtained were satisfactory, which yielded an average full width at half maximum (FWHM) and peak wavelength value (PWV) of 4.6 nm and 691.39 nm, respectively. Overall, the proposed method enabled a simple, low-cost, high-throughput approach for the fabrication of fine patterns on glass for various optical applications.

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